Bulletin
of
The Geological Society of America

VOLUME 58 September 1947 NUMBER 9

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Subscription $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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WAVE EROSION ALONG THE SOUTHERN CALIFORNIA COAST. By F. P. Shepard and U. S. Grant IV

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BULLETIN OF THE GEOLOGICAL SOCIETYOF AMERICA
VOL. 58, PP. 803-820. SEPTEMBER 1947

BIOGEOCHEMICAL PROSPECTING FOR COPPER AND ZINC

BY H. V. WARREN AND C. H. HOWATSON

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ABSTRACT

Agriculturists have long been interested in the minor-element content of trees and lesser plants and of the soils in which they grow. The authors have been interested in the relation of plants to ore deposits and have carried on in British Columbia a series of investigations which indicate that the zinc and copper content of some trees and lesser plants may reflect, to a striking extent, the presence of zinc and copper concentrations in the underlying soils or rock formations.

INTRODUCTION

Investigations into the role of botany in relation to subsurface geology were commenced at the University of British Columbia in 1945. Mr. and Mrs. Dorbils started the work; through Professor W. H. Gage, Chairman of the Committee on Prizes, Scholarships, and Bursaries, they offered the University the "Dorothy and William Dorbils Essay Prize in Botany and Geology." This was gratefully accepted, and, with the aid of a Special Research grant for "Botany and Sub-surface Geology" made available by the Board of Governors of the University of British Columbia, field work was commenced under the general direction of the senior author in the spring of 1945.

After consultation with the Departments of Botany and Agronomy a qualified and experienced botanist, Mr. J. W. Warden, was engaged to collect 200–250 samples from

various trees and lesser plants in several mining districts. The districts were chosen to include some samples from areas over known ore bodies and some from areas where it was known that no ore bodies existed. Collections were made during the spring and early summer of 1945.

During the 1945–1946 academic year the junior author investigated various analytic procedures; a survey was made of some of the more readily available literature in this general field, and equipment and supplies were obtained. These included a Wiley Mill and a first-class thermostatically controlled furnace. Mr. R. N. Williams made analyses of about 100 samples.

This paper lays no claim to completeness. It is merely a report of progress which, insofar as some of the results are most encouraging, may stimulate work elsewhere in this interesting and, for the geologist, little-explored field.

ACKNOWLEDGMENTS

The list of persons to whom the authors are indebted is long, and without these persons the work described herein could never have been attempted. The authors are particularly indebted to the following in addition to those mentioned in the body of the paper: Mr. C. P. Browning, General Manager, Britannia Mining and Smelting Co. Ltd., Mr. R. W. Diamond, Vice-president and General Manager, The Consolidated Mining and Smelting Co. of Canada Ltd., Dr. H. T. James, Managing Director, Pioneer Gold Mines of B. C. Ltd., Mr. W. I. Nelson, Assistant General Manager, The Granby Consolidated Mining, Smelting and Power Co. Ltd., and Mr. A. B. Staples, Mine Manager, Highland-Bell Ltd. All these gentlemen on behalf of their respective companies not only co-operated in every possible way, but also permitted all the results to be made public. Dr. V. Dolmage also gave much useful advice and assistance. Various departments of the University of British Columbia co-operated with the Department of Geology and Geography in this work; assistance came chiefly from the Physics, Botany, Biology, Agronomy, Forestry, Chemistry, Poultry, and Horticulture departments. Professor J. Davidson, Dr. D. G. Laird, and Dr. V. C. Brink were especially helpful. Dean Daniel Buchanan assisted greatly be helping to make funds available from the Board of Governors. Mr. R. N. Williams made the analyses virtually at cost, and he, together with Mr. and Mrs. Dorbils, must be specially mentioned for the support and inspiration they have given us.

Last, but not least, the authors wish to express their indebtedness to Commander (E) T. R. D. Munro, R.N., and Squadron Leader T. B. Wood, R.C.A.F., who during an Atlantic crossing found the time to check all our available calculations.

PREVIOUS WORK IN THE FIELD OF BOTANY AND EXPLORATION OF "TRACE" ELEMENTS

Much work has been done by agronomists, horticulturists, and botanists on the occurrence of "trace" elements in soils and plants. However, it would appear from the literature that, with the notable exception of a few Scandinavian workers, geologists have paid little attention to the relationship between botany and subsurface geology. Geologists familiar with the copper belt in Northern Rhodesia have known that specific vegetation can be correlated with particular formations, but little or no

quantitative results of these studies have been published. Of the few who have done such work, V. M. Goldschmidt appears to have been outstanding. For many years it has been customary for geographers in Great Britain to note the marked relationships between various botanical assemblages and the underlying geological formations. Geologists, although recognizing these relationships in a qualitative way, have apparently not tackled the problem quantitatively.

In some areas there may be no direct correlation among the "minor"- or "trace"-element content of trees and lesser plants, the soils in which they grow, and the parent rock from which the soil in part at least, may be derived. In Canada everything is further complicated by glaciation. However, in view of the relatively small amounts of such trace metals as copper and zinc in glacial drift, as compared with the amounts involved in ore bodies, there is every reason to hope that glaciation, although it may complicate, will not prevent effective investigations in what may be termed the field of biogeochemistry.

In addition to carbon, hydrogen, oxygen, and nitrogen, many elements are now known to play important roles in plant life—sulphur, phosphorus, iron, aluminium, boron, cobalt, calcium, magnesium, manganese, silicon, zinc, copper, sodium, selenium, potassium, and molybdenum. Some of these elements are known to be essential to plant life and growth, but others appear merely to be tolerated, and if present in excess they may kill some plants. Actually, the function of many of these elements in plant growth is not yet known. The following examples show how important some of these "minor" or "trace" elements are to plant and animal life.

Increased plant growth has been reported on many of the peat and muck soils in the United States and other countries where the soils have been treated with copper salts (Allison *et al.*, 1927).

Zinc compounds have been applied to soils to prevent "frenching" on citrus fruits, "rosetting" on pecans and apples, "little leaf" on peach and grape-vine, and "yellows" on walnut (Holmes, 1943).

Copper deficiencies in pastures and consequently in animals are constantly associated with "falling disease" in the cattle of the southwestern part of Western Australia (Bennets *et al.*, 1941).

The "Grand Traverse" or "Lake Shore" disease in Michigan cattle is essentially due to cobalt deficiencies (Killham, 1941).

"Pining" in sheep has been corrected by the administration of cobalt and cobalt-rich fertilizers to the pasture soils (Stewart *et al.*, 1941).

Some English herbage, containing a relatively large amount of molybdenum, if fed to cattle, causes a failure of milk, loss of condition, and even death (Ferguson *et al.*, 1938).

Certain plants indicate the presence of concentrations of particular elements in a soil. Heckel (1899) stated that *Polycarpaea spirostylus* (Carnation, or Pink family) so frequently contains copper that in Australia its growth is considered an indication of copper in the soil. Similarly *Viola calaminaria* (Violet family) indicates the presence of zinc.

Bateman and Wells (1917) found that *Rosa Woodsi* (wild rose), *Equisetum variegatum* (horsetail) and *Dasiphora fruticosa* (Bush cinquefoil) thrived in a copper-

tailing region where willow, alfalfa, and red clover had been killed by the increased mineral concentration. The plants growing in the copper-rich region contained from 62 to 6210 parts per million of copper; while willow, red clover, and grasses growing in a normal copper-free area of the same vicinity contained no detectable copper. Bateman has concluded that, because some plants are able and others are unable to adjust themselves to a new environment, a decided selective ability is indicated.

Prat and Komarek (1934), investigating the mineral contents of plants, found that in soils containing 1–33 per cent copper the species *Agrostis alba* (red top grass) and *Melandrium silvestre* (Caryophyllaceae family) contained from 0.2 to 3.25 per cent copper in their ash.

The mineral content of plants varies with the species and with the organs of the individual plants. Gamelin (1937) investigated 57 trees and 7 shrubs of the order Pinales (pines) of Quebec. He found that the manganese concentration varied inversely with the iron and that the highest manganese content was in the leaves, then progressively less in the bark, twigs, heart wood, fruits, and sapwood. Black spruce and tamarack contained most manganese, and white cedar the least.

Robinson (1943) found that the leaves of hickory trees growing on soils derived from granite and gneiss contain more rare earths than do leaves from other species growing on the same soils, and more than leaves from hickory trees growing on other soils. Analyses of hickory leaves from a tree growing on a pegmatite vein of the Moorfield Mine, Amelia, Va., showed a concentration of the rare-earth group of oxides amounting to 0.2 per cent of the dry weight of the leaves (Robinson, 1938).

The mineral concentration in the leaves of various species changes during the growing season—a fact not appreciated by the authors when arranging for their collections. McHargue and Roy (1932) found that the copper and zinc content of leaves increased with age of the tree, and Robinson (1943) found that mature hickory leaves have a higher rare-earth content than young leaves. It was thought that the mineral content of the leaves might migrate to the branches during the autumn, but ter Meulen and Ravenswaay (1935) have shown that, at least for molybdenum, there is no such migration. It may well be that this holds true for other elements.

The acidity or alkalinity of a soil influences the assimilation of mineral matter by plants. Delorme (1939) concludes that a calcareous soil apparently is a limiting factor on the absorption of manganese but that an acid soil may not favor assimilation in every case. The quantities of alumina present in hickory leaves vary from a few hundredths of 1 per cent in neutral soils to 1.5 per cent in acid soils (Robinson, 1938).

The composition of the parent material has a varying influence on the mineral content of a soil, depending on the conditions during the soil formation. According to Holmes (1943) there would be less copper and zinc held in the soil under acid than under basic conditions. Robinson *et al.*, (1939) found that Desert, Chernosem, and Prairie soils are usually high in boron, while soils of the Coastal Plains and Podsols are low in this element. The difference in the boron content of these soils may, however, be the result of uneven distribution of boron in the parent geological formations. Robinson's analyses show that the difference between the soils repre-

sents the difference in content of primary minerals, particularly tourmaline, in the parent rock, although the evidence presented does not exclude the possibility of the formation of an acid-insoluble secondary boron mineral.

Plants have been used extensively in the United States as indicators of seleniferous soils. They are defined as plants which contain significant amounts of selenium during all or a major part of their annual growth and thrive only in its presence (Beath *et al.*, 1939a). The main indicators are all species of *Stanleya* (Princesplume), *Oonopsis* (Goldenweed), *Xylorrhiza* (Aster), and many species of *Astragalus*. In South Dakota one formation, the Niobrara, and the soils derived from it are consistently seleniferous. The Lower Sharon Springs member of the Pierre shale also is consistently high in selenium, but this formation resists weathering, rarely forms soils, and vegetation is seldom found on it. Further studies (Beath *et al.*, 1939b) are believed to demonstrate that numerous geological formations from the late Paleozoic to Quaternary can support native seleniferous plants, which are found rooted in both igneous and sedimentary rocks, including monzonite, limestone, and shale.

Many of the more rare elements have been found in coal and coal ash. Milner (1929) records the occurrence of gold in coal from Cambria, Wyoming, silver in black carbonaceous shale, and vanadium in coal ash from Scotland, peat ash from North Carolina, and coal from Yauli, Peru. Uranium has been detected in anthracite bitumen from Sweden. Goldschmidt (1943) has also found many rare elements in coal.

The above examples indicate clearly that in many cases there is a relationship between the mineral content of the plants, soils, and parent rock. Goldschmidt (1943) emphasized this relationship as follows:

> "When the investigation is extended to cover a whole forest one may recognize local differences in the composition of the subsoil by noting differences of rare elements in the leaves of various trees.... It has, however, been shown by experiments carried out in Sweden and Finland, that ore deposits are in many cases indicated by a positive test on the ashes from the leaves of trees."

Lundberg (1944) is reported to have put leaf analyses to practical use as another tool in his geophysical prospecting in Canada and the United States. Unfortunately, while Lundberg's own papers (1940; 1941) draw attention to the value of biogeochemical prospecting they give little in the way of quantitative results.

Stiles (1946) has published a book containing a great deal of the available information on trace elements in plants and animals. Any person contemplating investigations in this field should familiarize himself with the contents of this book, which the authors have found to be full of valuable information.

OBJECTIVES OF PRELIMINARY INVESTIGATIONS

As is readily realized, this type of research is expensive and can be carried out only partly in the laboratory. Travel and field expenses are necessarily high, and analyses are expensive. Consequently, our primary objective was to show, at least possible expense, whether or not geochemical prospecting justified a series of costly researches. It was hoped not only that the results of these further researches would be of scientific value, but also that they might be useful in developing the resources of British Columbia.

Secondary objectives included discovering the general distribution of some of the selected minor elements and determining the more promising lines along which further research might be directed.

The most difficult problem is obtaining satisfactory control samples. This will eventually be accomplished by collecting representative suites from as many areas as practicable and relating these suites with the pH and other soil features, the geology of the underlying rocks, the general physiography, the season at which the samples are taken, the age of the trees concerned, and also some of the combinations of mineral elements involved in each sample.

Nevertheless, in spite of what, in the light of our present knowledge, appears to have been a haphazard method of collection, the results, and particularly those given in Tables 1, 3, and 7, show that both copper and zinc enter into the various organs of trees and lesser plants in varying amounts. They also demonstrate some correlation between the amounts of these elements in a plant, especially in the case of leaves and cones, and the presence or absence of important concentrations of copper and zinc in the vicinity. Glaciation may complicate but does not obscure this relationship. Boron also should be investigated in this way, because, not only is it definitely related to some ore bodies but it plays a vital role in plant life.

METHOD OF ANALYSIS

As the feasibility of employing geochemical methods in prospecting was being investigated, it was desirable to ascertain whether or not normal assaying technique could be employed. Consequently the analyst was given no hint as to the possible copper or zinc content of a sample. He was supplied with approximately 100 grams of air-dried plant material which was numbered but otherwise unidentified.

The analytical methods employed were essentially those used in normal assaying. Stock reagents and distilled water were employed, and blanks were run with every 10 samples. However, extra precautions were taken to prevent contamination. The following procedure was carried out.

100 grams of air-dried plant material were ashed in clay crucibles at 600°C. No precautions were taken to prevent loss of volatiles. The resulting ash was weighed and then treated with aqua regia. Concentrated sulphuric acid was then added, and the solution evaporated to fumes. The residue was dissolved in water, and the solution boiled.

This solution was neutralized with ammonium hydroxide. The iron, aluminium, and occluded salts were filtered out. This precipitate was dissolved in sulphuric acid and reprecipitated with ammonium hydroxide and again filtered out. An excess of ammonium persulphate was added to both filtrates to complete the precipitation of manganese as manganese dioxide. The precipitate was allowed to settle over night, then filtered and washed thoroughly with water. The filtrate was acidified with sulphuric acid and boiled for 10 minutes. Then an excess of sodium thiosulphate solution was added until all the copper was precipitated. The precipitate was filtered and washed with hot water. The paper containing the copper subsulphide was then dried and ignited at low temperature. The resulting

residue was taken up in concentrated nitric acid and evaporated to a volume of 1 cc. Ten cc. of water were added. The excess acid was neutralized with sodium acetate, and a small amount of sodium fluoride was added. The solution was cooled to room temperature, and an excess of potassium iodide was added. Titration was then carried out with sodium thiosulphate solution equalling 1 mg. of copper per cc. of solution.

The filtrate from the copper precipitation was neutralized with ammonium hydroxide, then acidified with hydrochloric acid, and a slight excess added. This solution was brought to boiling and titrated with potassium ferrocyanide solution of a strength equal to approximately 1 milligram of zinc per cc. of solution. Uranium acetate was used as an outside indicator. The blanks were made up by using the same amount of reagents as in the normal determinations, and appropriate deductions were then made from the amount found in the unknowns.

The results seemed to be sensitive to within about 1 part in 1 million of ash. Analyses reported negative (−) do not indicate that the sample contained no copper or zinc, but rather that no satisfactory determination could be made on the amount of sample analyzed.

DETAILED RESULTS

GENERAL CONSIDERATIONS

The tables present the most important results, together with the authors' interpretations and comments thereon. The following abbreviation has been used throughout: p.p.m. = parts per million.

Positive or metal-bearing samples are those taken from ground known to be cupriferous or adjacent to outcrops of proven copper ore; negative or metal-free samples are those taken from areas in which sufficient mining or exploration has been done to assure beyond reasonable doubt the absence of any copper concentrations in the vicinity. Presumably there are always some copper and zinc in the soil, otherwise these metals would not appear so consistently in the leaves and fruit of trees and lesser plants; consequently the designations positive and negative must be considered as only relative.

Negative areas might have been chosen at random. However, it will be appreciated that, since a great portion of British Columbia is covered with soil and glacial drift, the only areas which can be assumed to be negative are those in which extensive development has proven this to be the case. Indeed, one of the prime reasons for undertaking this work was to find out whether the metal content of trees and lesser plants could be used as a guide in prospecting for drift-covered ore bodies. As much care, therefore, was taken in choosing the negative as the positive areas, particularly when it was early realized that all samples contained some copper and zinc. In short, for our purposes it was most important that the amount of copper and zinc in the so-called negative areas be established so that significant variations might be appreciated.

The tables and comments represent the information collected from three of the five camps at which collections were made; the remaining two camps are omitted, as in one case the original collections proved to be too small and in the other no

satisfactory positive area could be established. Two camps—Britannia and Texada Island—may be considered as copper-rich and zinc-poor; and the third, Chapman Camp, as zinc-rich and copper-poor. Samples from both positive and negative areas in each of these camps were collected.

TABLE 1.—*Britannia copper analyses*

		Positive Copper in ash	*Negative* Copper in ash
		p.p.m.	*p.p.m.*
Tsuga Mertensiana (Mountain Hemlock	Cones (on ground)	34560	1540
Tsuga Mertensiana	Bark	2060	210
Abies amabilis (Fir)	Twigs and leaves	1400	430
Vaccinium spp. (Blue-berry)	Leaves	2000	570
Alnus sinuata (Green Alder)	Leaves	25650	310
Echinopanax horridus (Devil's Club)	Leaves	12810	290
Average copper contents p.p.m.		13080	560

BRITANNIA (COPPER)

Samples were obtained from this camp after a careful choice of positive and negative areas had been made by W. T. Irvine, Geologist for the Britannia Mining and Smelting Company. Collecting was done during the third week in June.

Table 1 shows the copper content of six positive and six corresponding negative samples. The plants are referred to in the text hereafter by their common names.

All the Britannia samples were also analyzed for zinc because, although there were negligible amounts of this element in the areas from which the samples were taken, nevertheless it was thought advisable to obtain the zinc analyses for purposes of comparison with analyses taken from other negative and positive areas. In making these determinations it was necessary to remove any manganese which might be present, so this element also was determined. The relative amount of iron present was noted, but no attempt was made to determine it quantitatively. The results of the manganese and iron analyses are not given here.

Table 2 shows the zinc content. Two samples not given in Table 1 are reported. They came from a positive copper area, but as there was no corresponding negative sample available they were omitted from the table of copper results. Little can be concluded from Table 2 except that the average zinc content for the whole area is 740 p.p.m. of ash. The averages suggest that the zinc content of the ash from the positive copper areas is higher than that from the negative; however, in view of so many unsatisfactory blanks, this latter conclusion is without significance.

CHAPMAN CAMP (ZINC) (SULLIVAN MINE NEAR KIMBERLEY, B. C.)

Although Chapman Camp is close to and associated with one of the great zinc mines of the world, it has been difficult to select satisfactory positive and negative samples. After discussing the problem with Mr. H. R. Banks, Superintendent of the Sullivan Concentrator, and Dr. C. O. Swanson, Geologist for the Consolidated Mining and Smelting Co. Ltd., a selection was made of areas which might be considered reasonably satisfactory. Collecting was done in early June.

Table 3 shows the zinc content of nine positive and nine corresponding negative samples.

Four other positive samples have been analyzed from Chapman Camp, but their negative counterparts are not available at the time of writing. The results are:

TABLE 2.—*Britannia zinc analyses*

		Positive (copper) Zinc in ash	*Negative (copper)* Zinc in ash
		p.p.m.	*p.p.m.*
Mountain Hemlock	Cones (on ground)	220	1920
Mountain Hemlock	Bark	330	—
Amabilis Fir	Twigs and Leaves	440	—
Blueberry	Leaves	500	470
Devil's Club	Leaves	870	—
Green Adler	Leaves	2560	490
Tsuga heterophylla (Western Hemlock)	Leaves	—	
Thuya plicata (Giant Cedar)	Sprays	2490	
Average zinc content p.p.m.		930	480

Average zinc content in p.p.m. for all Britannia samples = 740.

TABLE 3.—*Chapman Camp zinc analyses*

		Positive Zinc in ash	*Negative* Zinc in ash
		p.p.m.	*p.p.m.*
Pinus contorta (Lodgepole Pine)	Cones (on tree)	19780	6750
Pinus contorta	Bark	2780	1960
Populus trichocarpa (Black Cottonwood)	Leaves	7760	—
Populus trichocarpa	Wood	—	370
Salix sp. (Willow)	Bark	490	40
Larix occidentalis (Larch)	Leaves	2540	2390
Populus tremuloides (Aspen)	Leaves	4000	1640
Larch	Bark	2690	1130
*Shepherdia canadensis** (Soopolallie)	Leaves	1090	740
Average zinc content p.p.m.		4570	1560

* This plant is well known in Western Canada. The name is an Indian one and is sometimes spelled "Sopolallie."

Chapman Camp contains negligible quantities of copper (Table 4).

		Positive Zinc in ash
		p.p.m.
Larch	Cones	11430
Willow	Leaves	2070
Aspen	Bark	490
Aspen	Wood	—
Average zinc content p.p.m.		3500

Insofar as one may draw conclusions from the small number of samples, it would seem that the negative zinc plants contain more copper than do the positive.

TEXADA ISLAND (COPPER)

It proved difficult to obtain satisfactory samples from this camp. No outcrops of ore bodies could be found, and it was therefore necessary to take samples of

TABLE 4.—*Chapman Camp copper analyses*

		Positive (zinc) copper in ash	*Negative* (zinc) copper in ash
		p.p.m.	*p.p.m.*
Lodgepole Pine	Cones (on tree)	210	1000
Lodgepole Pine	Bark	260	930
Black Cottonwood	Leaves	160	320
Black Cottonwood	Wood	—	40
Willow	Bark	—	170
Larch	Leaves	90	340
Aspen	Leaves	220	290
Larch	Bark	380	130
Soopolallie	Leaves	120	130
Larch	Cones	460	
Willow	Leaves	180	
Aspen	Bark	100	
Aspen	Wood	—	
Average copper content p.p.m.		170	370

Average copper content p.p.m. for whole of Chapman Camp samples = 250.

vegetation from the vicinity of old mine dumps. Also, the deposits are replacements in limestone, and, as the surrounding country rock is limestone, there is less chance of migration of copper than there might be where the host rock is not so calcic. The negative samples were taken from the top of a rock quarry where extensive development has shown no sign of copper. Collecting was carried out in the middle of May. Mr. C. Cox, Mine Manager at the Little Billy Mine, kindly assisted in selecting the best places for collecting.

Table 5 shows the copper content of 12 positive and 12 corresponding negative samples.

All the Texada Island samples were also run for zinc. The quantity of zinc in the Texada Island ores in the vicinity from which these samples were taken is negligible. Nevertheless, it was felt that these analyses would establish a normal zinc content for vegetation in a negative zinc area.

It is gratifying to note that, in spite of so many unknown factors, the average zinc content of 740 p.p.m. approximates the average zinc content of Britannia (870).

COPPER MOUNTAIN AND BEAVERDELL

Besides the three camps two others were visited, Copper Mountain and Beaverdell, the former in the hope of obtaining good positive copper samples, and the

TABLE 5.—*Texada Island copper analyses*

		Positive Copper in ash	*Negative* Copper in ash
		p.p.m.	*p.p.m.*
Pseudotsuga taxifolia (Douglas Fir)	Cones	10310	370
	Bark	930	360
	Leaves and Trash	250	50
	Wood	3210	1200
Giant Cedar	Bark	—	330
	Leaves and Trash	540	270
	Wood	1270	—
Western Hemlock	Bark	360	910
	Leaves and Trash	290	490
	Wood	1600	—
Pteridium aquilinum (Bracken)		1110	250
Holodiscus discolor (Ocean Spray)		570	—
Average copper content p.p.m.		1700	350

TABLE 6.—*Texada Island zinc analyses*

		Positive (copper) Zinc in ash	*Negative (copper)* Zinc in ash
		p.p.m.	*p.p.m.*
Dougals Fir	Cones	360	—
	Bark	—	4910
	Leaves and Trash	320	600
	Wood	2140	—
Western Red Cedar	Bark	—	670
	Leaves and Trash	270	400
	Wood	580	4800
Western Hemlock	Bark	1040	490
	Leaves and Trash	60	270
	Wood	3600	—
Bracken		120	—
Ocean Spray		710	—
Juniperus scopulorum (Rocky Mountain Juniper)	Wood	480	—
Average zinc content in p.p.m.		740	1010
Average zinc content in p.p.m. for all Texada Island samples			870

latter because ores containing silver and zinc were known to occur there. No satisfactory positive areas were available at Copper Mountain, but the averages obtained from several plant samples do indicate the copper and zinc content of plants in an area which may be considered negative. An average of 20 samples from Copper Mountain gave an ash content of 290 p.p.m. for copper and of 1700 p.p.m. for zinc.

Beaverdell ore contains negligible amounts of copper and so may be taken as a negative copper area. Ten samples averaged 300 p.p.m. of copper. Three positive

zinc samples carried 2130 p.p.m. in contrast to three corresponding negative samples which ran to 770 p.p.m. of zinc. No silver analyses are yet available.

SUMMARY

Table 7 sums up the results obtained in the five camps.

In two camps the amount of copper in the ore is negligible—namely, Chapman Camp and Beaverdell. At Texada Island and Copper Mountain satisfactory

TABLE 7.—*Summary of results in various camps*
(All figures express p.p.m.)

	Copper		*Zinc*	
	Positive	Negative	Positive	Negative
Britannia	13080	560		740
Chapman Camp		250	4570	1560
Texada Island	1700	350		870
Copper Mountain		290		1700
Beaverdell		300	2130	770

negative areas were obtainable. At Britannia samples were taken over what was believed to be barren ground, although the results were higher than average. Both positive areas gave considerably higher results than the highest negative area.

The two positive zinc areas carry more of this mineral than the highest negative area. This is surprising considering the relatively small amount of zinc present at Beaverdell.

Therefore the ash of a random selection of botanical samples may carry from 200 to 600 p.p.m. of copper. If a group of samples runs over 1000 p.p.m. of copper, concentrations of copper probably will be found in the vicinity. The validity of this assumption will have to be tested by carrying on similar studies in many other camps with varying climatic and geological conditions.

There is a less satisfactory collection of material available for zinc. Nevertheless there are two copper camps, Britannia and Texada Island, where the amount of zinc in the collecting areas is small enough for them to be considered negative zinc areas. Also, the negative samples from Beaverdell may be considered satisfactory. The parallelism between the average zinc content in the ashes of these three areas is too close to be ignored: Britannia 740, Texada Island 870, and Beaverdell 770.

These figures, inadequate though they may be for the drawing of any final conclusions, do suggest two working hypotheses. In general plants carry a little more than twice as much zinc as they do copper, and on an average they carry an ash content of from 700 to 900 p.p.m. of zinc. Any reversal in this "normal" relationship may indicate copper or zinc mineralization. Furthermore, if the ash of plants from any area contains more than twice the "normal" amount of zinc—say more than 1500 p.p.m.—then that area must, in the light of the evidence at present available, be considered as one of possible zinc concentration.

Thus, in spite of some apparent contradictions, there appears to be support for

the belief that biogeochemistry may well be used as an aid in tackling the problems involved in searching for hidden bodies of zinc and copper. It may be possible to present both prospector and geologist with a new and useful tool. In any event, these preliminary studies indicate the need for more detailed investigation.

TABLE. 8.—*Ash content of some typical air-dried materials*
All figures are in percentages

	Soopolallie	Lodgepole Pine	Douglas Fir	Aspen	Larch	Willow	Alder
Wood		.25 .25	.14 .25 .15 .15 .15	.25			
Wood and Bark	.45 .35			.85 .65		1.80 1.25	
Bark		1.25 1.15 1.35 1.40	.54 .55 1.25 1.10	2.55	1.30 1.55	4.05 5.65	
Leaves	4.60 3.80			5.15 6.90	3.90 4.22 3.55	6.90 7.48 5.50	2.73 4.20
Leaves and Twigs	1.15	1.85 1.65	2.55 2.00				
Cones		4.35 .95 .40 .50	1.93 1.60 .65		1.25 1.30 .90 1.40		Catkins 3.90 3.85

PERCENTAGE OF ASH IN VARIOUS BOTANICAL SPECIMENS

This question was considered so that in the future samples might be taken of a weight suitable for the particular problem to be investigated. Table 8 serves merely as a guide, because obviously many factors have to be remembered, such as the time of year when collecting, and the temperature and degree of drying to which the specimen is subjected before analysis.

Table 8 shows that in the specimens analyzed wood has the lowest ash content and leaves the highest. Bark and cones appear to lie between wood and leaves; their true position is obscured by the varying water content of the samples at the time they were ashed.

Two samples of Devil's Club, not given in Table 8, showed an ash content of 8-9 per cent, and these results were doubly interesting because this plant also showed signs of being a particularly sensitive indicator of copper.

VARIATIONS IN THE COPPER CONTENT OF THE ASH OF VARIOUS BOTANICAL SPECIMENS

In this exploratory study an attempt was made to determine which part of a plant or tree was most indicative of mineral variations in its source of food supply.

TABLE 9.—*Copper content of the ash of various parts of some trees and plants*

p.p.m.

+ and − indicate positive and negative areas.

	Soopolallie	Lodgepole Pine	Douglas Fir	Aspen	Larch	Willow	Alder
Wood		+ −	+3210	+ −			
		−1080	−1200				
			+ −				
			−1130				
			+ −				
Wood and Bark	+ −			+120		+ −	
	−60			−260		−60	
Bark		+ −	+930	−90	−380		
		−320	−360		−130	−170	
		−260	+80				
		−930	−560			−330	+25650
Leaves	−260			−220	−200	−130	−310
	−130			−290	−1800	−180	
					−340		
Leaves and Twigs	−300	+700	+250				
		−350	−50				
							Cathins
Cones		−240	+10310		−640		−400
		−460	−370		−230		−280
		−1000	+610		−110		
		−1100			−460		

Space does not permit a complete tabulation, but Table 9 gives the results for those species of which samples from more than one locality are available.

Table 9, unfortunately, does not include Devil's Club or Mountain Hemlock; both the leaves of the former and the cones of the latter carried, at Britannia, more than 1 per cent of copper in their ash; indeed, the ash after burning contained so much copper that it had a blue tint.

Thus, although the evidence is largely negative, it seems clear that the leaves and cones are more sensitive to variations in the availability of copper than is wood or bark. Also, although either wood or bark may contain too little copper to be detected by the analytical methods employed, the leaves and cones always contain some copper, even in the undoubtedly negative areas. Furthermore, the cones

seemingly carry more copper than do other parts of the tree. This last conclusion also may be drawn from the results of assays of Mountain Hemlock cones from Britannia. It has been claimed that copper is essential to the manufacture of chlorophyll, and thus it is not surprising to find it in the leaves; its role in cones is

TABLE 10.—*Zinc content of the ash of various parts of some trees and plants*
Symbols are as shown in Table 9

	Soopolallie	Lodgepole Pine	Douglas Fir	Aspen	Larch	Willow	Alder
Wood		−2000	−2140	−			
		− −	− −				
			−5000				
			−5000				
			−6670				
Wood and Bark	+2780			−2640		−1390	
	−2140			−1540		−1400	
Bark		−1200	− −		+2690	+490	
		− −	−4910		−1130	−40	
		+2780	−800				
		−1960	−450				
Leaves	+1080			+4000	+1050	+3820	−2560
	−740			−1640	+2270	−770	−490
					−2390	+2070	
Leaves and Twigs	+1480	−2840	−320				
		−1060	−60				
Cones		−850	−360				Catkins
		+19780	− −		−960		−570
		−6750	+610		+920		+1440
		+7500			+1330		
					+11430		

not known, at least to the writers. If this copper is essential and is universally found in leaves, its source in many areas remains a mystery. The source of this copper offers an interesting and useful subject for research. Another profitable line of research would be to experiment by adding copper to various soils and comparing the copper content of the trees growing in the treated area with those in untreated areas.

The zinc content of these same samples is shown in Table 10.

The only correspondence between the zinc content and copper content is that the cones seem to show the greatest concentrations of both. The zinc content of wood ash appears extremely variable, and even in some negative areas the wood shows a high zinc content. It is also noticeable that the zinc content of leaves, although variable, does not show the same concentration as does copper. The

various barks also show great variation in their zinc content. Obviously zinc and copper differ greatly in their physiological role in plant life.

OTHER ELEMENTS NOTED DURING ANALYTICAL WORK

Calcium, magnesium, sodium, aluminium, and silicon were all present, and complete ash analyses will not only be of general interest but may also be used to interpret general subsurface geology, in contrast to the problem of searching for hidden ore bodies. Spectrographic methods of analysis were also investigated during the past year. Although the results obtained have not been yet prepared for publication, for some elements spectrographic analytical methods will probably prove practical. Silver (McDonald, 1946), present in minute quantities, was identified in some cones by spectroscoping these cones directly.

SOME SECONDARY RESULTS

Secondary results indicate that:

(1) Copper and zinc play different roles in plant growth.

(2) Cones and needles of *Tsuga Mertensiana* (Mountain Hemlock), *Pseudotsuga taxifolia* (Douglas Fir), *Larix occidentalis* (Larch), and *Pinus contorta* (Lodgepole Pine) all offer possibilities for the detecting of unusual concentrations of copper and zinc.

(3) Leaves of *Echinopanax horridus* (Devil's Club), *Alnus sinuata* (Green Alder) and *Salix sp.* (Willow) all show ability to indicate the presence in their vicinity of abnormal amounts of copper or zinc.

(4) The wood of the various trees carries the least total mineral content, and the green leaves or needles the most. The fruit and bark contain amounts between these two extremes.

(5) In the samples examined, zinc seems on the average to be twice as abundant as copper.

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Manuscript Received by the Secretary of the Society, November 13, 1946.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 821-832, 2 FIGS. SEPTEMBER 1947

ORIGIN OF A SCAPOLITE METAGABBRO IN BUCKS COUNTY, PENNSYLVANIA

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ABSTRACT

In Bucks County, Pennsylvania, a body of limestone was invaded by pre-Cambrian gabbro with practically no contact action. Much later, dynamic metamorphism transformed the gabbro into a metagabbro, composed chiefly of andesine and hornblende, which replaced the original augite. Lighter bands in the metagabbro, containing oligoclase feldspar, indicate the introduction of hydrothermal solutions.

Within the quarry some of the metagabbro is interbanded with a scapolite metagabbro, consisting mainly of diopside and scapolite. The chemical composition of the two rock types is similar despite their distinct mineral suites. The scapolite metagabbro is considered the result of recrystallization of the metagabbro which took place at the time of dynamic metamorphism, aided by the introduction of small amounts of hydrothermal solutions. Coarse-grained, crosscutting bands of scapolite and diopside, isolated masses of scapolite and diopside, and oligoclase-diopside masses are also present within the limestone. Throughout, the composition of the scapolite is the same.

All the rock masses within the limestone are boudins which lie along three parallel zones. This indicates that the original gabbro intruded the limestone in dikes, which, during later dynamic metamorphism, were drawn out into boudins and rotated in the limestone during a plastic stage of the deformation. Joints and a fault, roughly perpendicular to the regional foliation, suggest a still later brittle stage in the deformation, but the uniformity of the scapolite composition implies that the plastic and brittle stages of the deformation were connected, and both were generally contemporaneous with the hydrothermal activity.

INTRODUCTION

Van Artsdalen's Quarry, 1.7 miles N. 25° W. of the intersection of Neshaminy Falls and U. S. Highway No. 1, in Bucks County, Pennsylvania, has been mapped on the Trenton quadrangle of the U. S. Geological Survey (Bascom *et al.*, 1909b) as a body of limestone surrounded by gabbro. The quarry is 100 by 150 feet with walls 5 to 30 feet high.

Abandoned in 1880, the quarry was famous for fine mineral specimens, and it continued to attract amateur mineral collectors and scientific workers, such as Jefferis Genth, Rand, and Kemp. Rogers (1858) reported the following minerals from there: scapolite, sphene, diopside, graphite, augite, and several varieties of mica.

In 1892, Kemp sent two students to study the area. They reported an occurrence of norite near the quarry, since some hypersthene was found in the surrounding metagabbro. Kemp (1892) believed that the minerals in the limestone were the result of contact metamorphism between the plutonic rock mass and the limestone. Since Kemp's paper, there has been no serious consideration of the structural relationships or the geologic origin of the rock types here.

ACKNOWLEDGMENTS

The writer wishes to thank Drs. E. H. Watson and Dorothy Wyckoff, professors in geology at Bryn Mawr College, and Mr. Samuel G. Gordon, of the Academy of Natural Sciences in Philadelphia, for their advice, assistance, and encouragement in working on this problem.

The writer is grateful to Miss Edith Lanman, Department of Chemistry, Bryn Mawr College, for her chemical analyses of the two metagabbros.

GENERAL GEOLOGY

The rock surrounding the quarry has been variously referred to as gneiss, gabbro, and plagioclase amphibolite. Armstrong (1941) infers that it is an injected rock of the same type as that found farther west at Bryn Athyn. The injected amphibolite extends eastward to Trenton and westward beyond the Schuylkill. A mile north of the quarry it is overlapped by Triassic sediments, and 1½ miles south of the quarry it is bordered by a ridge of Cambrian Chickies quartzite. To the northwest, the gneiss complex is unconformably overlain by this same quartzite (Bascom *et al.*, 1909a, Pl. 6; Bascom *et al.*, 1909b, Pl. 2).

Bascom (1909b) believed that the metagabbro was a pre-Cambrian gabbro which injected both the Baltimore gneiss and the Wissahickon mica gneiss. E. H. Watson (personal communication) has shown that the gabbro is the older rock; in areas where it has been injected by granitic material the hybrid rock is named Baltimore gneiss. This gneiss complex and the older gabbro in this region are pre-Cambrian; near by both are overlain by the Cambrian Chickies quartzite.

ROCK TYPES AND MINERALS

The quarry is in a coarsely crystalline calcitic marble. Quantitative and qualitative chemical tests on the calcite of this rock show it to be free of magnesium. The

magnesia, minor SiO_2, and other impurities possibly present in the original sediment could be responsible for the formation of diopside and other minerals scattered through the limestone (Harker, 1932; Taylor and Williams, 1936). Rare, well-formed, pale-blue crystals of apatite have been found. Red-brown phlogopite is present either in scales or in small six-sided crystals. Flakes of a bright-green muscovite mica occur at some places with the phlogopite. Silky white masses of wollastonite were once present in the quarry, but in the present exposures this mineral is found only in microscopic quantity as laths and interstitial aggregates. These minerals very likely were formed by recrystallization during dynamic metamorphism which also produced pressure twinning in the calcite. Other minerals in the limestone are small crystals of pyrite, and graphite in flakes, crystals, and thin bands. Within some masses of phlogopite there is a deep blue-green chlorite (penninite), derived probably from the phlogopite during a period of hydrothermal activity, which also produced small bands and masses of white tremolite in the diopside crystals. Only in the northeast corner of the quarry is the limestone more or less fine-grained and lacking other minerals. Everywhere else the grains are 3 to 10 mm. long. This coarseness of crystallization seems to bear no relation to other rock types in the quarry, since coarser marble is found both at the contacts with these rocks and isolated from them. All the minerals, other than the calcite, in the limestone make up less than 2 per cent of this rock.

A variation diagram, indicating both the modal composition and the age sequence of the various rock types, has been constructed (Fig. 2). The rock outside the quarry (Fig. 2, Nos. 71, 70) is a metagabbro composed mainly of hornblende, augite, and plagioclase, with some minor hypersthene. The metagabbro exhibits light and dark bands and is probably an injected rock. In the dark bands, the percentage of hornblende is higher, and the plagioclase is andesine (An_{46}). The light bands contain oligoclase (An_{28}), some microcline, and a minor amount of quartz. Some of the lighter bands are pegmatitic, with blue quartz and microcline as the main constituents. These pegmatites are not abundant. The metagabbro is gneissic, fine-grained, equigranular, and has an average grain size of 0.5 mm.

The hornblends of the metagabbro shows a strong pleochroism, with X = yellow, Y = yellow-orange, Z = brown. Its composition is not uniform, as is shown by the range of refractive indices. In thin sections the grains appear unaltered and not fractured, in contrast to the augite, which occurs in fractured and partially replaced grains. These may be the remains of the pyroxene of the original gabbro, and the hornblende of the present rock may have replaced the augite. The augite is pleochroic, light to medium green. Some hypersthene, with characteristic pink to green pleochroism and parallel extinction, occurs in the metagabbro in the northeast corner of the quarry.

Within the quarry, the metagabbro, which is believed to have invaded the limestone, also is banded though diopside takes the place of some of the hornblende and augite (Nos. 69, 63). Some of these bands are a fine- to medium-grained gneissic rock, which may be called a scapolite metagabbro (No. 57b). The bands vary from half an inch to 2 or 3 inches in width. In these bands, scapolite substitutes for the plagioclase, and hornblende is represented by diopside. Accessory minerals are

sphene, phlogopite, calcite, and wollastonite. The scapolite metagabbro has an average grain size of 0.5 to 0.6 mm., though in some bands the grains are as large as 2 to 3 mm. In these coarser-grained bands, which are only several inches wide, the scapolite metagabbro is massive and crosscuts the finer-grained gneissic rocks.

Very coarse-grained scapolite-diopside rock, with crystals 3 to 10 mm. in size, is present in isolated masses in the walls of the quarry (Nos. 72, 65, and 59), as are also scapolite-feldspar and feldspar aggregates. All these coarse-grained masses contain sphene crystals, some as much as an inch across, diopside, and small phlogopite crystals. The feldspar in these coarse aggregates is oligoclase (An_{24-28}) with a small amount of perthitic microcline. Many of the large oligoclase masses have a bluish iridescence which caused them to be mistaken for labradorite by early collectors There is some alteration of the plagioclase to sericite.

The diopside in the scapolite metagabbro is pale yellow green to medium green and appears to range in composition from almost pure diopside to augite, since the indices of refraction increase with the extinction angles. Where $Z \wedge c$ exceeds 45° the mineral may be considered augite. The grains have veinlets of tremolite along the cleavage cracks and are surrounded by coronas of this same material.

The scapolite, both in the scapolite metagabbro and the coarse-grained scapolite-feldspar masses, is remarkably uniform in composition. Throughout the quarry, its refractive indices are constant and indicate a composition of wernerite (Me_{73}).

STRUCTURE

The body of limestone is small, probably underlying not more than a few acres; in an east-west direction the walls of the quarry expose the enclosing metagabbro. Because of the heavy vegetation, the north-south dimensions of the limestone cannot be found, but there is no evidence of its outcropping anywhere outside the quarry except about 30 feet to the northwest along the entrance path. West of the quarry, the residual fragments are all metagabbro, with dark and light bands.

The various intrusions and aggregates of rocks other than limestone which are exposed within the quarry are all in boudins[1] or schlieren, isolated from each other (Fig. 1). These rock masses lie along three general zones which strike N. 30° E., suggesting that the original gabbro invaded the limestone as dikes. Other assumptions would make the gabbro sedimentary fragments in the limestone, or postulate a hydrothermal origin for the limestone, both of which appear highly unlikely. The existence of more of these dikelike intrusions can only be inferred, since the main portion of the limestone has been removed by quarrying.

Most of the limestone is massive, but on the west wall and in the center of the south wall of the quarry it has a somewhat foliated appearance because here the graphite

[1] The term "boudinage" was first suggested by Lohest (1922) as applying to a phenomenon observed in the Bastogne, in southeast Belgium. Under compression less competent beds flow and more competent beds are separated into masses which are compressed longitudinally into "boudins". The boudins were likened to large sausages strung out side by side. The term was applied originally to symmetrical arches which were not separated by the incompetent rock above and below them, But it has been extended to include what the British geologists call "phacoidal structures" (Peach, 1907), which are surrounded by enveloping layers of the incompetent rock

Cloos (1941) writes of dolomite boudinage as revealed in the limestone of the Howellville quarry in Pennsylvania, and Quirke (1923) describes the phenomenon in detail.

flakes are arranged with a preferred orientation or in thin bands which strike roughly northeast-southwest and dip steeply northwest. In the northwest corner a band of graphite outlines a recumbent fold which is overturned to the southeast and plunges 25° SW. All through the quarry, the orientation of the graphite flakes shows the limestone to be conformable to the outlines of the boudins in it and indicates strikingly the plastic flow of the limestone.

The strike of the foliation in the limestone ranges from N. 32° E. to N. 85° W. but in general is parallel to the regional trend. However, the strike and dip of the foliation in the boudins does not everywhere coincide with the regional trend. This suggests that these rock masses were rotated as they were separated from each other during the plastic stage of deformation of the limestone. On the south wall a metagabbro boudin has been broken off from a larger metagabbro mass to which it probably was connected and rotated into a different direction.

On the west side of the quarry, a fault, paralleled by two joints, strikes N. 81° E. and dips 79° NW. The fault truncates and displaces a boudin 7 feet to the east. The strike of the fault and of the joints is roughly perpendicular to the strike of the veins of crosscutting, coarser-grained scapolite metagabbro.

The boudinage is evidence of a plastic stage of deformation of the limestone, and the fault, joints, and crosscutting coarser-grained bands seem to indicate a later brittle stage of deformation. The material in these coarse bands probably entered and crystallized in the shear zones produced during the brittle state of deformation. However, since the composition of the scapolite is everywhere the same, these two periods of deformation appear to be related.

PETROGRAPHY AND CHEMICAL ANALYSES

Certain optical properties for nearly all the minerals present appear in Table 1. 2 V was measured with a universal stage on some of the minerals and estimated or calculated from the refractive indices on others.

The interbanding of the metagabbro with the scapolite metagabbro is recognizable even more easily within some thin sections than in the hand specimens. The two mineral suites are quite distinct, and 20 thin sections made from specimens collected within and outside the quarry (Fig. 1) were measured with an integrating stage. Sixteen of these measurements were plotted to form the variation diagram (Fig. 2). No scapolite metagabbro was found outside the quarry or on the rim. Within the quarry, both scapolite metagabbro and metagabbro occur, and the diagram indicates the sharp demarcation of the two mineral suites, the scapolite substituting for the plagioclase, the diopside for the hornblende.

Chemical analyses of the metagabbro (No. 69) and the scapolite metagabbro (No. 45) are remarkably similar (Table 2) considering their diverse mineral composition. If the scapolite metagabbro is derived from the metagabbro, the main constituents needed to effect the change chemically are a slight increase in TiO_2, FeO, and K_2O, with a small loss in SiO_2 and MgO. The hydrothermal activity, which produced the felsic bands in the regional metagabbro, could have introduced the first three oxides. The slight loss of SiO_2 could have been influenced by the CO_2 of the surrounding limestone (Daly, 1933, p. 497), though the exact physical-chemical conditions needed to

TABLE 1.—*Mineralogic data*

Mineral	Color	Form	Index	2V	Extinction angles
Apatite	colorless to pale-blue	small prismatic crystals	ε1.63		
Andesine (An_{38})	colorless	anhedral			
Augite (in metagabbro in quarry)	medium-green	anhedral	α1.690 β1.696 γ1.715	58° (measured)	Z ∧ c 45°–52°
Augite (in metagabbro outside quarry)	medium-green	anhedral	α1.710 β1.715 γ1.730	60° (calculated)	Z ∧ c 45°–52°
Augite (in scapolite metagabbro)	pale-yellow-green to medium-green	subhedral to anhedral	α1.705 β1.711 γ1.730	60° (calculated)	Z ∧ c 45°
Calcite	colorless	anhedral			
Chlorite (Penninite)	deep blue-green	scaly masses	α1.574 β1.580 γ—	2° (estimated)	
Diopside (in limestone)	pale-green	euhedral to subhedral	α1.670 β1.677 γ1.700	58° (calculated)	Z ∧ c 37°
Diopside (in scapolite metagabbro)	pale-yellow to yellow-green	anhedral	α1.673 β1.680 γ1.701		Z ∧ c 37°–43°
Garnet (grossularite)	colorless to pink	euhedral to subhedral	1.76		
Graphite	black	flakes or small crystals			
Hornblende (in quarry	yellow-brown	lathes or anhedral	α1.641 β1.654 γ1.663	78°–82′ (measured)	Z ∧ c 16°–23°
Hornblende (outside quarry)	brown	lathes or anhedral	α1.670 β1.686 γ1.696	78° (measured)	Z ∧ c 16°–25°
Hypersthene	pleochroic pink to green	anhedral	α1.713 β1.725 γ1.730	65° (calculated)	‖ extinction

TABLE 1—*Concluded*

Mineral	Color	Form	Index	2V	Extinction angles
Microcline	colorless	anhedral			
Muscovite	bright-green	scale or small masses	α1.595 β1.600 —	22° (measured)	
Oligoclase	colorless	anhedral			
Phlogopite	coppery-brown	six-sided crystals or scaly masses	— β1.598 γ1.598	0–3° (estimated)	
Pyrite	brassy, iridescent	small octahedra or pyritohedra			
Quartz	colorless	anhedral			
Scapolite	colorless to pale-yellow	anhedral	ω1.553 ϵ1.583		
Sericite	colorless to pale-yellow	scaly masses in plagioclase			
Sphene	light- to medium-brown	large crystals to anhedral grains		30°–35° (estimated)	
Tremolite	colorless to pale-green	anhedral	α1.609 β1.621 γ1.627	84° (measured)	Z ∧ c 17°
Wollastonite	white	fibrous masses	α1.620 — —	38° (measured)	Z ∧ c 2°–3°

produce this syntexis are unknown. The analyses show mainly that very little material need be introduced to alter the mineral composition.

A chemical analysis (made for Miss Florence Bascom by F. A. Genth, Jr., but apparently unpublished) of the regional metagabbro 1½ miles west of Van Artsdalen's quarry is included in Table 2. Norms were calculated for the chemical analyses and also for the average "world gabbro" (Daly, 1933, p. 17). Nepheline appears in the norm of the metagabbro of the quarry and is greater in the norm of the scapolite metagabbro. The percentage of albite decreases from the norm of the regional metagabbro to the norm of the metagabbro of the quarry and disappears in the norm of the scapolite metagabbro. This variation may signify some syntexis or reaction between the original intruding gabbro and the limestone, which lowered the percent-

age of SiO_2 and raised the percentage of CaO in the metagabbro of the quarry. However, the original intrusion of gabbro did not produce the unusual mineral suite in the scapolite metagabbro, since both metagabbro and scapolite metagabbro are

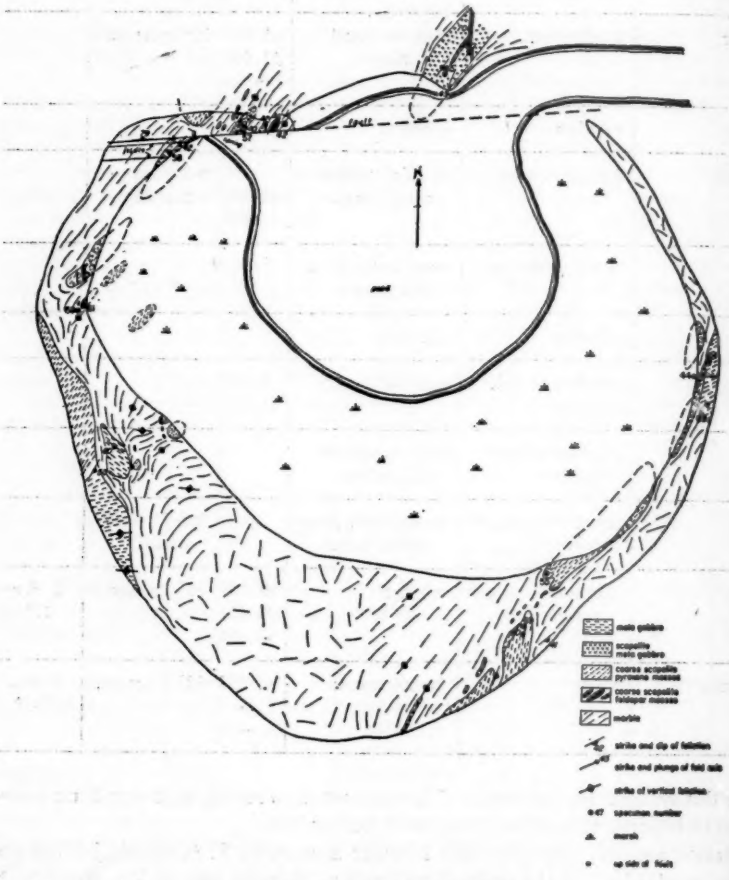

FIGURE 1.—*Map of the quarry*
Showing the various rock types and structural elements.

found within the quarry. Probably, later hydrothermal activity caused another reaction or syntexis with the formation of the scapolite metagabbro and other scapolite-bearing rocks. The composition of the scapolite in the conformable scapolite bands, in the crosscutting coarser scapolite metagabbro bands, and in the pegmatoid scapolite-diopside boudins is identical. This is good evidence for connecting the hydrothermal activity with the period of dynamic metamorphism.

ORIGIN

The field relations indicate that the limestone is the oldest rock. Bascom (1909b) correlated it with pre-Cambrian Franklin limestone, which outcrops 70 miles to the northwest in New Jersey, and suggested that the Bucks County limestone represented a remnant of that formation left by erosion. Kemp (1892) also thought that the

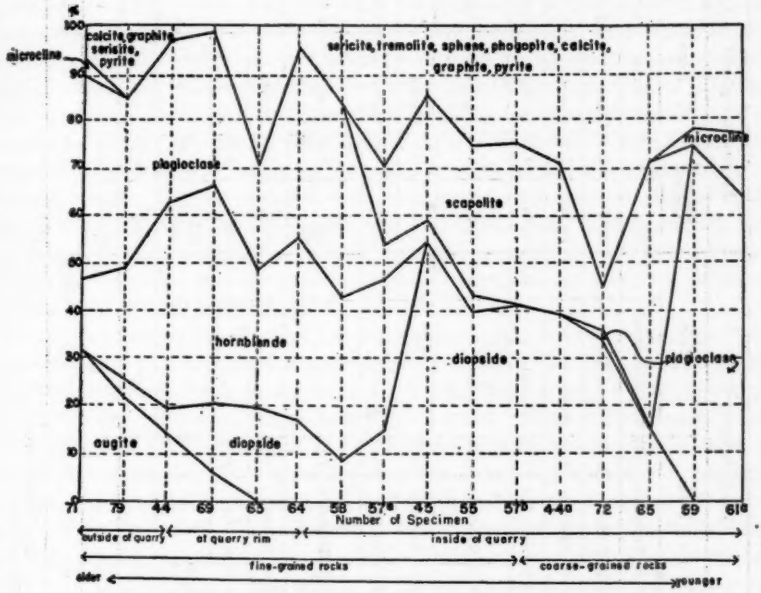

FIGURE 2.—*Variation diagram of modal composition*

limestone was pre-Cambrian and believed that the limestone which is so greatly developed in New Jersey extends also into Pennsylvania, but lies far beneath the surface. The small Van Artsdalen limestone body may have become involved in the igneous rock during the passage of the latter upward. The structural relations observed between the limestone and the igneous rock do not favor this latter view; the supposition that the limestone is a roof pendant is more reasonable. That it originally was a sediment is suggested by its relative uniformity and by its high graphite content. Not only are there flakes and grains of graphite scattered through it, but in many places bands of graphite a quarter to half an inch thick extend for many feet.

The pre-Cambrian age of the limestone is implied by the intrusion into it of gabbro which has been considered also pre-Cambrian because it disconformably underlies the Cambrian Chickies quartzite.

The regional metagabbro is chemically very similar to Daly's world gabbro, except that it is somewhat higher in FeO. In the immediate vicinity of the limestone body, there is a decrease in SiO_2 in the metagabbro and increase in CaO (Table 2), but in

TABLE 2.— *Chemical analyses, norms, and modes*

No. 45, Scapolite metagabbro						No. 69, metagabbro						Regional metagabbro‡				Average world gabbro (Daly)			
Chemical analysis*		Norm		Mode		Chemical analysis*		Norm		Mode		Chemical analysis		Norm		Chemical analysis		Norm	
SiO_2	43.55	Orthoclase	9.45	Plagioclase(An_{37})	0.7	SiO_2	46.72	Orthoclase	2.23	Plagioclase(An_{61})	30.6	SiO_2	50.12	Orthoclase	3.34	SiO_2	48.24	Orthoclase	5.00
TiO_2	2.32	Anorthite	27.25	Scapolite(Me_{65})	32.4	TiO_2	0.88	Albite	14.14	Hornblende	52.0	TiO_2	2.10	Albite	25.15	TiO_2	0.27	Albite	21.48
Al_2O_3	16.01	Nepheline	11.92	Tremolite	3.5	Al_2O_3	15.41	Anorthite	28.10	Augite	2.1	Al_2O_3	15.11	Anorthite	26.13	Al_2O_3	17.88	Anorthite	34.75
Fe_2O_3	2.22	Sodalite	0.41	Muscovite	2.5	Fe_2O_3	1.82	Nepheline	5.40	Diopside	13.8	Fe_2O_3	3.37	Diopside	20.55	Fe_2O_3	3.16	Diopside	15.85
FeO	9.16	Diopside	31.87	Diopside	55.0	FeO	7.17	Sodalite	0.36	Calcite, Graphite, Pyrite	1.5	FeO	8.32	Hypersthene	12.22	FeO	5.95	Hypersthene	5.78
MnO	0.10	Olivine	10.07	Sphene	4.3	MnO	0.14	Diopside	28.67			MnO	tr.	Quartz	1.86	MnO	0.13	Olivine	8.92
MgO	7.26	Magnetite	3.25	Calcite	0.6	MgO	9.70	Olivine	15.12			MgO	5.44	Magnetite	4.87	MgO	7.51	Magnetite	4.64
CaO	13.53	Ilmenite	4.41	Graphite, Apatite, Wollastonite	1.0	CaO	13.29	Magnetite	2.55			CaO	10.35	Ilmenite	3.95	CaO	10.99	Ilmenite	1.82
Na_2O	2.83	Calcite	0.30			Na_2O	3.05	Ilmenite	1.67			Na_2O	3.01	Pyrite	.27	Na_2O	2.55	Apatite	0.28
K_2O	1.59					K_2O	0.37	Calcite	0.80			K_2O	0.65			K_2O	0.89		
H_2O^+	0.70					H_2O^+	0.62					H_2O^+, H_2O^-	1.40			H_2O^+, H_2O^-	1.45		
H_2O^-	0.10					H_2O^-	0.09												
Cl	0.27					Cl	0.19					P_2O_5	0.07			P_2O_5	0.28		
CO_2†	0.11						0.35					$S_{(FeS_2)}$	0.15						
Total...	99.69		98.93		100.00		99.76		99.04		100.00		100.07		98.34		100.00		99.52

* Chemical analysis made by Miss Edith Lanman, Dept. of Chemistry, Bryn Mawr College.
† CO_2 content determined by Adolph Meier, Dept. of Geology, Bryn Mawr College.
‡ Metagabbro from 1½ miles west of Van Artsdalen's Quarry.

these differences are not great enough to postulate a large-scale contact metamorphism at the time of the pre-Cambrian intrusion into the limestone.

The boudinage and the way the limestone wraps around the individual boudins indicate that during later dynamic metamorphism the limestone became highly plastic. In certain boudins, metagabbro and scapolite metagabbro are similarly deformed and intimately banded together with gneissic structure, showing that some of the alteration of the one rock to the other occurred early in the period of regional deformation. Some of the boudins contain narrow, crosscutting veins of similar pegmatoids, possibly emplaced during the brittle stage of the dynamic metamorphism, which produced the fault and joints also crosscutting the general trend of foliation. Coarse, pegmatoid boudins of scapolite-diopside-feldspar rock are presumed to be of the same age as the cross-cutting pegmatoid veins, because of their similar texture and grain size. The scapolite-bearing rocks probably were formed during some hydrothermal activity. The occurrence in boudins of metagabbro and scapolite metagabbro, and of pegmatoid scapolite-diopside and scapolite-feldspar masses, and the fact that the scapolite in all the rock types is the same, suggest that the hydrothermal activity, the formation of these various rocks by recrystallization, and the deformation were roughly contemporaneous.

If there were two periods of activity, one in which the gabbro intruded the limestone and reacted with it to produce the scapolite metagabbro, and a later metamorphism of the limestone by hydrothermal solutions, resulting in the masses of scapolite, diopside, and feldspar, certain questions cannot be answered. Why is the composition of the scapolite, if it has been formed at two different periods, so remarkably uniform throughout the quarry? Why are there bands of scapolite metagabbro throughout the boudins of metagabbro in the quarry and not merely at the contact of the metagabbro and the limestone? Though these two rock types look much alike in the field, their different mineral composition and their intimate structural relationship are easily seen in thin sections. Also, why is the percentage of CaO practically the same in the scapolite metagabbro as in the metagabbro? If one were formed from the other by contact action with the limestone, the percentage of CaO in the later rock should be much higher.

During dynamic metamorphism the limestone became plastic and completely recrystallized into a marble. The temperature and pressure during the metamorphism were elevated enough so that wollastonite, diopside, and phlogopite formed from the impurities in the limestone. Consequently, in view of the very similar chemical character of the scapolite metagabbro and the metagabbro, this same elevation of temperature and pressure plus small amounts of hydrothermal solutions could aid in the recrystallization of one rock from the other. Contact metamorphism and the introduction of large amounts of granitic material into limestone can produce, and have elsewhere produced, the unusual mineral suite present in this quarry. Nevertheless, it is obvious that, under suitable physical-chemical conditions, these same minerals can be formed by recrystallization of existing material with the introduction of very little new material. Also, the formation of the mineral suite from the other is considered to have taken place not during the pre-Cambrian gabbro intrusion into the limestone, but during later regional deformation roughly contemporaneous with a period of hydrothermal activity.

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Bryn Mawr College, Bryn Mawr, Penna.
Manuscript Received by the Secretary
of the Society, January 6, 1947

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 833-842 SEPTEMBER 1947

UPPER LIMIT OF THE JURASSIC SYSTEM

BY ARMANDO F. LEANZA

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ABSTRACT

This paper deals with the zonal paleontological sequence of the uppermost Jurassic and lower Cretaceous strata on the strength of the Argentine ammonite fauna. Some misleading interpretations regarding the so-called *Spiticeras damesi* and *Parodontoceras callistoides* zones are pointed out, and some significant species actually found in them are discussed. Thus evidence is provided toward clarification of several interpretations formerly advanced about the Upper Jurassic boundary as a whole.

INTRODUCTION

During the last decade or so, more or less extensive references are frequently found in important papers to some biozones of the Tithonian-Neocomian succession in Argentina and to their position in the general chronological sequence. In Argentina, between 1921 and 1933, different paleontologic levels were discriminated by Gerth, on the basis of species of ammonites, in a series of publications throughout which he put forward his views with remarkable constancy. These opinions took firm root in Argentina and abroad and attained considerable importance as a starting point and source of reference for later investigations. On the basis of Gerth's opinions European and North American stratigraphers and paleontologists, engaged in the task of correlating the Argentine ammonite fauna and those of other countries, accepted the successions of paleontologic zones established by Gerth for our ammonite-bearing levels.

As in few other places in the world, the southern part of the Province of Mendoza offers opportunity to examine a thick series of sediments of a remarkably uniform character, containing an exceptionally rich and varied fauna, the species of which show that a marine environment persisted practically unchanged throughout the whole area from the basal Tithonian to the end of the Hauterivian. Many fossil-bearing levels may be identified in the vertical range of these sediments, in which species and genera of ammonites follow each other in a perfectly traceable evolutionary sequence; the fauna, as a whole, varies in a gradual, but obvious manner.

Recent studies by the author on the ammonites of the Upper Jurassic and Lower Cretaceous formations of Sierra Azul (Leanza, 1945) now enable him to discuss the opinions set forth by different authors concerning the actual position of the *Parodontoceros callistoides* zone as the lowest Cretaceous unit. The conclusions expounded in this paper are used freely.

To clear up the question of the age of the *Parodontoceras callistoides* zone, it will be necessary to state also the precise limits of the *Spiticeras damesi* zone, by recording the species actually found within it.

Both *Parodontoceras callistoides* and *Spiticeras damesi* have been found, with absolute certainty, only in the Argentine. For this reason, when these two forms are quoted as index fossils of different paleontologic levels, authors have been compelled to base their conclusions on the stratigraphic data afforded by the few existing monographs on Argentine ammonites. Unfortunately, however, such data do not always agree with the facts, and, because these paleontologic zones correspond precisely to levels closely approaching the Jurassic-Cretaceous boundary, their accurate comprehension is essential in order to place the above-mentioned boundary.

The first part of this paper will be devoted to correcting what, in the author's opinion, is not altogether accurate in these monographs. The second part considers the upper limit of the Jurassic system.

The author is indebted to Dr. Ralph W. Imlay for having sponsored this contribution and for submitting it for publication.

ARGENTINE BERRIASIAN-VALANGINIAN, ACCORDING TO GERTH

To facilitate reading of the present paper the paleontologic table of the Argentine Berriasian-Valanginian as originally given by Gerth (1925, p. 128) is given here. Determinations of the different fossils will be maintained as they were indicated by him.

Valanginian

NEOCOMITES (LYTICOCERAS) TRANSGREDIENS (STEUER) ZONE: *Neocomites* (*Lyticoceras*) *regalis* Bean f. *andina* Gerth, *Neocomites senilis* Gerth, *Neocomites inflatus* Gerth, *N. inflatotuberculatus* Gerth, *Blanfordiceras australe* (Burckhardt).

SPITICERAS DAMESI (STEUER) ZONE: *Astieria laticosta* Gerth, *Spiticeras fraternum* (Steuer), *S. bodenbenderi* (Steuer), *S. laeve* Gerth, *S. groeberi* Gerth, *S. latior* (Steuer), *Andesites loncochensis* (Steuer), *A. fasciculatus* (Steuer), *A. argentinus* (Steuer), *A. turgidus* (Steuer), *Neocomites crassituberculatus* Gerth, *Acanthodiscus wichmanni* Gerth, *A.* aff. *hystricoides* Uhlig.

Berriasian

THURMANNIA FRAUDANS (STEUER) ZONE: *Himalayites grandis* (Steuer), *H. egregius* (Steuer), *Berriasella multipartita* Gerth.

STEUEROCERAS PERMULTICOSTATUM (STEUER) ZONE: *Thurmannia* aff. *thurmanni* Pictet var. *allobrogica* Kilian, *T. keideli* Gerth, *Steueroceras subfasciatum* (Steuer), *S. rotundatum* Gerth, *Berriasella callistoides* (Behrendsen).

SPITICERAS ACUTUM GERTH ZONE: *Spiticeras hauthali* Gerth, *S.* cf. *conservans* Uhlig, *Thurmannia duraznensis* Gerth, *T. discoidalis* Gerth, *Berriasella beneckei* (Steuer).

STEUEROCERAS KOENENI (STEUER) ZONE: *Steueroceras ellipsostomum* (Steuer), *S. striolatissimum* (Steuer), *S. steueri* Gerth.

KILIANELLA BURCKHARDTI (MY.-EYM.) ZONE: *Berriasella alternans* Gerth, *B. inaequicostata* Gerth, *B. spinulosa* Gerth.

SPITICERAS DAMESI ZONE

Gerth defined two paleontologic zones within the Upper Valanginian: that of *Spiticeras damesi* below, and "*Lyticoceras*" *transgrediens* above.

In his monograph Weaver (1931, p. 57) pointed out that *Spiticeras damesi* was associated with "*Lyticoceras*" *transgrediens* in the field and inferred that the two zones established by Gerth could be joined into a single paleontologic zone, which he proposed to designate as the "*Astieria*" *laticosta* zone.

In view of Weaver's observations, Gerth (1933) partially modified his conclusions and, with no further work in the field, considered that Weaver's paleontologic table uniting his two zones into one could apply only to the Territory of Neuquen, as in the southern Mendoza his own two zones could be traced clearly.

Recent studies show that the *Spiticeras damesi* zone includes numerous species of *Cuyaniceras* Leanza (*Odontoceras transgrediens* Steuer group = *Steueroceras* Cossmann emend. Spath not *Steueroceras* Cossmann emend. Burckhardt) which of late has been frequently ascribed to the *Lyticoceratan* age of Lower Hauterivian.

In the Río Salado region (Southern Mendoza), especially in beds which outcrop along the right bank of a southern tributary of that river (Arroyo Cieneguita) collections have been made recently which indicated that, contrary to Gerth's opinion, beds with *Spiticeras damesi* include different species of *Cuyaniceras*. To support this statement examples have already been given (Leanza, 1945) which definitely prove the true position of the *Cuyaniceras* beds.

In the bed numbered "1773" of Mallín Redondo, *Spiticeras damesi* (Steuer) and *S. fraternum* (Steuer) are associated with *Cuyaniceras acanthicum* Leanza and *Cuyaniceras groeberi* Leanza.

In the Arroyo del Yeso, the bed marked with the letter "l" contains:

Cuyaniceras transgrediens (Steuer)
Cuyaniceras mendozanum Leanza
Cuyaniceras raripartitum (Steuer)
Cuyaniceras groeberi Leanza
Cuyaniceras extremum Leanza
Cuyaniceras argentinum Leanza
Cuyaniceras acanthicum Leanza
Cuyaniceras inflatum (Gerth)
Neocomites (?) *inaequicostatus* Leanza

In the same cross section of Arroyo del Yeso, bed "m", situated 7 meters above bed "l", contains the following species:

Spiticeras damesi (Steuer)
Spiticeras singulare Leanza
Spiticeras aff. *bodenbenderi* (Steuer)

Bed "l-m", situated between the beds marked "l" and "m", yielded:

Neocomites regularis Leanza
Spiticeras bodenbenderi (Steuer)

These facts are sufficient to demonstrate incontrovertibly that the forms of *Cuyaniceras* correspond, essentially, to the same horizon which contains *Spiticeras damesi*.

In connection with the *Spiticeras damesi* zone (including that of *Cuyaniceras transgrediens*) there arises the question, discussed by Spath in several publications, whether the Valanginian stage exists in Argentina. Spath, when referring the *S. damesi* zone to the Berriasian and the next higher zone—in Gerth's succession—to a *Lyticoceratan* age, *i.e.*, basal Hauterivian, stated that "there would appear to be no

true Valanginian at all in the Andes, which might explain the absence of forms of *Olcostephanus*" (Spath, 1939, p. 129).

As to the absence of *Holcostephanus* in the ammonitic fauna of Argentina, this can no longer be sustained since, with Gerth's publication (1925), we have now another species which corresponds to this genus. Up to the present, four forms of *Holcostephanus* have been found in the Argentine: "*Astieria*" *laticosta* Gerth, "*Astieria*" *curacoensis* Weaver, *Holcostephanus auritus* Leanza, and *Holcostephanus midas* Leanza.

In their respective biostratigraphic tables of the Tithonian-Neocomian of Argentina, Gerth (1925, p. 128) and Weaver (1931, p. 56) placed the two species of "*Astieria*" in the Upper Valanginian, considering them as coming from the same beds which contain *Spiticeras damesi* (Steuer).

By taking into consideration this association, which does not in reality exist, some authors assign all the faunistic elements of which it is composed, including the two species of "*Astieria*", to the Berriasian, and, as corollary, these same authors state that in Argentina no Valanginian beds are represented.

Field evidence demonstrates, however, that the four species of *Holcostephanus* mentioned above are always found stratigraphically higher than the sediments which contain *Spiticeras* and, futhermore, that in certain parts of the Territory of Neuquèn an extraordinary thickness of sediments is interposed between the levels which contain, respectively, *Holcostephanus* and *Spiticeras*.

Therefore, the *Spiticeras damesi* zone, according to Gerth's interpretation (= "*Astieria*" *laticosta* zone, according to Weaver), which has been accepted by all investigators who have dealt with this problem, may be divided into two levels: a lower, that of *Spiticeras damesi*, composed of the forms included by Gerth and Weaver in this zone, with the exception of *H. laticosta*, *H. curacoensis*, and *Lissonia riveroi;* and an upper level composed of the three latter species which may be referred to the Upper Valanginian for reasons given below.

At least two of the four species of *Holcostephanus* in Argentina correspond to the subgenus *Rogersites* Spath (*Holcostephanus modderensis* Kitchin group).

To fix the position of the two Argentine species (*Holcostephanus midas* and *H. auritus* Leanza, 1944) it should be remembered that they are provided with lateral lappets at the aperture of the shell, of the same type as *Rogersites otoitoides* Spath from the Neocomian beds of Uitenhage (Spath, 1930, p. 149).

The genus *Holcostephanus* and the subgenus *Rogersites* are particularly abundant in the Middle and Upper Valanginian proper.

As to *Lissonia riveroi* (Lisson)[1], associated with *H. curacoensis* in the same bed, it tells us nothing about the age of the beds which contain it.

Another argument which can be brought forward in favor of the Valanginian age

[1] The genotype of *Lissonia*, i.e. *Hoplites riveroi* (Lisson, 1907, p. 51, Lám. VIII, figs. 2a–b), is a small fragment figured by Lisson in 1907. In spite of this circumstance, this fragment possesses such peculiar characteristics (ribs strongly bent toward the aperture in the external third of the flank, and a deep groove in the siphonal zone) that Spath's proposal to consider it as the type of a new genus is perfectly acceptable. Although the Argentine specimens undoubtedly correspond to *Lissonia*, inasmuch as they are identified as *Lissonia riveroi*, it is not possible to come to a satisfactory conclusion. Here the Argentine *Lissonia* is indicated as *L. riveroi* only to follow the rule implanted in this country. In Perú the *Lissonia riveroi* level has not been established, and it is not known with what ammonites this species is associated.

of beds containing *Holcostephanus* is that, in Sierra Azul, they are found above sediments which contain *Neocomites wichmanni* Leanza and *Thurmannites pertransiens* Sayn. The first of the species belongs to the "*Ammonites*" *neocomiensis* d'Orbigny group, which is very common in the European Valanginian, especially in the lower section. A very typical and common species found in the middle Valanginian of France is *Thurmannites pertransiens* Sayn.

Thus, the so-called *Spiticeras damesi* zone in the Argentine includes the "*Odontoceras*" *transgrediens* zone but not the beds containing *Holcostephanus curacoensis* and *Lissonia riveroi*, which may, strictly speaking, be referred to the Valanginian.

PARODONTOCERAS CALLISTOIDES ZONE

The zone of *Parodontoceras callistoides* in Argentina is mentioned for the first time by Krantz (1928, p. 49). This author, in accordance with his paleontologic determinations and the stratigraphic data which he obtained from the fossils forwarded to him by Gerth, distinguished the following fossiliferous horizons within the Upper Tithonian:

KOSSMATIA PSEUDODESMIDOPTYCHA KRANTZ ZONE: *Aulacosphinctes wilfridi* Burckhardt.
NEOCOMITES KAYSERI (STEUER) ZONE: *Berriasella oppeli* Kilian and *Andiceras acuticostum* Krantz.
PARODONTOCERAS CALLISTOIDES (BEHRENDSEN) ZONE: *Berriasella* (*Corongoceras*) *mendozanum* Krantz, *B.* (*C.*) *submendozanum* Krantz, *Berriasella duraznensis* Krantz, *B. argentina* Krantz, *B. subprivasensis* Krantz, and *Aspidoceras andinum* Steuer.

The association established by Krantz (1928, p. 49) with respect to the *P. callistoides* zone surely indicates a Tithonian age, as he says, for *Andiceras*, *Corongoceras*, and *Aspidoceras* are very characteristic of that age.

Gerth (1925, p. 128) mentions *P. callistoides* in association with *Substeueroceras permulticostatum* and *S. rotundatum*. In the author's (1945) paper on the ammonites of Sierra Azul reasons are given which permit the zones that Gerth indicated as Infravalanginian to be considered as Tithonian.

In the cross section of Arroyo del Yeso the bed marked with the letter "g" contains the following species of ammonites:

Parodontoceras callistoides (Behrendsen)
Micracanthoceras vetustum (Steuer)
Aspidoceras longaevum Leanza
Substeueroceras koeneni (Steuer)
Substeueroceras exstans Leanza

The association in the bed marked "g" is of extraordinary interest because it shows the genotype of *Substeueroceras* (*S. koeneni* Steuer) associated with *Parodontoceras callistoides*, indicating that both species lie together within the same level which, as it also contains *Aspidoceras* and *Micracanthoceras*, may be referred to the Tithonian.

Thus, although *P. callistoides* has ample vertical range, its presence having been noted in different horizons, even in those stratigraphically higher, it always corresponds to the Tithonian.

Kilian (1907, p. 185; table p. 287) mentions *P. callistoides* characterizing a paleontologic assemblage which he places as a horizon of the Berriasian (= Infravalanginian) below the *Subthurmannia boissieri* in southeastern France and in Andalucía, Spain. From an examination of the illustrations of the specimen deter-

mined by Kilian[2], one may conclude that it differs visibly from Behrendsen's form. These differences are mainly in the pattern of the ribs over the umbilical slope. In *P. callistoides* the ribs are strongly opisthoclinal in that sector, and the umbilical edge is very indefinite. (Cf. Leanza, 1945, pl. 5, fig. 6.) The umbilical slope is very slight, and this characterizes especially the genus *Parodontoceras*. In Kilian's example the ribs do not show the strong backward-arch over the umbilical slope which so characterizes the ribs of the true *P. callistoides*. Even with these slight differences Kilian's proposed identification should be discarded.

Dr. Ralph W. Imlay, of the U. S. Geological Survey, kindly informed the author that Mazenot (1939) "refers to *Hoplites callistoides* Behrendsen on many pages and definitely rejects Kilian's determination of the species for southeastern France".

UPPER LIMIT OF THE JURASSIC

Boswell (1929, p. 384), Muller (1941, p. 1439; table), and Muller and Schenck (1943, table p. 272–273), who took their ideas mainly from those earlier postulated by Spath (1923, p. 304; 1924, table facing p. 80), adopted the following scheme for the Tithonian-Berriasian sediments:

Berriasian	Zone of *Subthurmannia boissieri*	*Spiticeras latior*
	Zone of *Parodontoceras callistoides*	*Spiticeras damesi*
		Spiticeras acutum
Tithonian	Zone of *Berriasella privasensis*	*Berriasella delphinensis*
		Protacanthodiscus chaperi

The *Parodontoceras callistoides* zone in Argentina, which gives the type for this species, may be ascribed to the Tithonian and does not exist in the Infra-Valanginian in France, so that a true *P. callistoides* zone cannot be distinguished in Europe. The *Spiticeras damesi* zone in Argentina is always found perfectly separated from the levels which contain *Parodontoceras*, and, therefore, it cannot constitute a subzone of the *Parodontoceras callistoides* zone.

If the conception of Spath's, Muller and Schenck's, and Boswell's *P. callistoides* zone was reached by taking into account the form so designated by Kilian, there is no reason for a *P. callistoides* zone. Even if Kilian's form were not different from that of the Argentine, the fact of its being cited by this author (Kilian, 1907, table p. 287) in association with *Subthurmannia boissieri* in the eastern part of the Lower Alps would be no reason to differentiate the *P. callistoides* zone by a special name.

Spath (1924; 1929), Boswell (1929), and Muller and Schenck (1943) divide the Berriasian into two paleontologic zones: a lower, *P. callistoides*, and an upper, *S. boissieri*.

In the *P. callistoides* zone, these writers distinguish three subzones, from the bottom up, as follows: the *Spiticeras acutum*, the *Spiticeras damesi*, and *Spiticeras latior* subzones. There is no sense in this subdividision, since the species which gives its name to this zone is found only in the lower subzone (*Spiticeras acutum* subzone) and never with fossils of the other two subzones. The circumstance that, in numerous

[2] Kilian (1889, p. 661, pl. XXXI, figs. 3a–b) mentiones this species as *H. callisto* d'Orbigny, but later (1907, p. 139) he names it *H. callistoides*.

cross sections made in the field, *Spiticeras damesi* always appears much above that level in which *Parodontoceras* disappears should also be taken into account.

Gerth mentions *Parodontoceras callistoides* in the *Substeueroceras permulticostatum* zone, a species with which it can, in reality, be associated, but he does not mention it among the fossils of his zone with *Spiticeras damesi*, which he placed in the Upper Valanginian.

The only species of *Spiticeras* which, up to now, have been found along with *Parodontoceras callistoides* are *Spiticeras acutum* and *Spiticeras hauthali*, but these forms constitute a special group within the *Spiticeras*, because of the ogival-shaped section of its whorls, from an early age. Gerth mentions the other species of *Parodontoceras* (*P. beneckei* Steuer) along with the two species of *Spiticeras* just named.

All the stratigraphic research carried out in the Argentine allows us to state that the sediments which contain the *Spiticeras damesi* fauna are always found at a higher stratigraphic level than the one which contains *P. callistoides*. For this reason the interpretation proposed by Spath, Muller and Schenck, and Boswell maintaining that the *S. damesi* zone is enclosed within the zone of a higher order (*P. callistoides*) cannot be accepted.

Mazenot (1935, p. 253–255), in a brief communication, gave some information on the ammonitic fauna of the Jurassic-Cretaceous boundary of Central Europe and the Argentine, based on his examination of collections of the Universities of Munich and Goettingen, where important material from these regions is preserved.

The few lines which Mazenot dedicates to the Argentine fauna are destined to establish whether common species exist in the Alpine zone and our country. For example, he states that the attribution, on the part of Behrendsen (1891–1892) and Steuer (1897), of some Argentine ammonites to the Alpine forms cannot be maintained, as in the case of *Berriasella oppeli* Kilian and *Hoplites incompositus* Retowski. On the other hand, he concludes that *Hoplites subvetustus* Steuer should be synonymous with *Berriasella chomeracensis*. Mazenot's work contains no reference to *P. callistoides* as a species common to Argentina and Europe.

Arkell (1946) brings forward his estimable opinion on the Standard of the European Jurassic system. He (1946, p. 21) claims rights of priority for the *Virgatosphinctes transitorius* zone (Neumayr, 1871) over the *B. privasensis* and *B. callisto* zones proposed by Kilian in 1887 and 1895 respectively. On the basis of Mazenot's (1939) study Arkell disqualifies the subzones of *B. delphinensis* and *P. chaperi* distinguished in the upper and the lower part of the Tithonian, respectively, in Muller's (1941) Jurassic system scheme. In this case it should be mentioned that these subzones "now appear to be not worthless but upside down".

In the Argentine, Krantz (1928) made known to us in some detail the ammonitic fauna of the Tithonian and pointed out the presence of elements of Mediterranean fauna such as *Simoceras* and several species of *Berriasella*, associated with Indian types and elements belonging to the Russian Jurassic, like *Riasanites rjasanensoides* and *R. swistowianus*. Recently I have added to the Tithonian some paleontologic horizons situated immediately above the level containing *Windhauseniceras* Leanza (group of *Perisphinctes internispinosum* Krantz), and these horizons include most of the species belonging to the "*Odontoceras*" *koeneni* group (i.e., *Substeueroceras* Spath) and some *Himalayites* whose assignment to the Tithonian we have affirmed above.

Considering that the ammonite-bearing zones of the Upper Tithonian distinguished by Krantz correspond perfectly to the *Virgatosphinctes transitorius* zone (= *privasensis* zone), the fauna added here to the Tithonian could constitute a special paleontologic level, situated between the *V. transitorius* and the *Spiticeras damesi* zones, the latter being equivalent to the *Subthurmannia boissieri* zone.

Thus the horizons which contain *Substeueroceras* in the Argentine and Mexico (*see* Imlay, 1942; 1943) can be correlated, because of their stratigraphic position, with a level between the *transitorius* zone and that of the *boissieri*.

Although in Alpine Europe (especially in southeastern France) the limit between the Tithonian and Berriasian can be traced between *Subthurmannia boissieri* and *Virgatosphinctes transitorius*, in the Argentine it is placed between the *Spiticeras damesi* and the *Substeueroceras* zones[3].

Thus a new paleontologic zone in the uppermost part of the Tithonian is established, which, according to our actual knowledge, does not seem to occur outside of the Americas. In Mexico and Cuba, Imlay's important studies supply decisive arguments in favor of our hypothesis. In connection with this it is interesting to recall the association mentioned by this author (1942, p. 1426) in the Pinar del Río zone, western Cuba (Locality 5229 of the U. S. Geological Survey), where the following species are found: *Pseudolissoceras* cf. *zitteli* (Burckhardt), *Virgatosphinctes cristobalensis* Imlay, *V.* aff. *rotundidoma* Uhlig, *Corongoceras filicostatum* Imlay, *C.* cf. *filicostatum* Imlay, *Lytohoplites caribbeanus* Imlay, *Parodontoceras butti* Imlay, and *P. antilleanum* Imlay.

Whether the horizons containing *Substeueroceras* are equivalent in a chronologic sense to the highest part of the Alpine Tithonian is a matter which cannot be solved for the moment, but certainly they contain a highly specialized fauna, already closely resembling those of the oldest Cretaceous. If these levels with *Substeueroceras* could be correlated with the highest part of the *transitorius* zone, the apparent absence of *Substeueroceras* forms in the Alps could be explained on paleobiogeographic grounds.

Despite the facts that Arkell considers the assignment of the Rjasan beds to the Jurassic as heresy and that the supposed presence of *Riasanites rjasannensis* in the Alpine Tithonian has been made void by Mazenot, the occurrence in the Argentine of two forms which probably correspond to the genus *Riasanites* seems to confirm Spath's opinion that the beds mentioned correspond to the Tithonian, because *R. rjasannensoides* and *R. swistowianus* are found in Mendoza in sediments of undoubtedly Tithonian age below beds which yield, among other fossils, *Aspidoceras longaevum* Leanza.

Bogoslowsky's (1895) paper on the Rjasan beds (Khorochovian stage, Pavlow, 1900) illustrates an ammonite that Bogoslowsky named *Hoplites micheicus*. The figures are so like those of the Tithonian *Hoplites koellikeri* Haupt not Oppel (= *Corongoceras lotenoense* Spath) that one almost suspects them of specific identity.

[3] To the argument adduced referring the *S. damesi* to the Infra-Valanginian may be added that afforded by the discovery of a species of *Subthurmannia* in the locality of Casa Pincheira. This form, discovered by Dr. Dessanti, was found in a level about 20 meters above a bed containing *S. damesi*.

If Bogoslowsky's form really pertains to the genus *Corongoceras*, this is a conclusive argument with which to fix the Rjasan beds, the position of which has led to lively polemic and will continue to do so.

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Manuscript Received by the Secretary of the Society, October 9, 1946.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 58, PP. 843-918, 13 PLS., 21 FIGS. SEPTEMBER 1947

OÖLITE DEFORMATION IN THE SOUTH MOUNTAIN FOLD, MARYLAND

BY ERNST CLOOS

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ABSTRACT

The South Mountain fold is a large asymmetrical overturned anticline. Its axial plane dips to the southeast, and its crest is the western slope of South Mountain. Cleavage dips steeper in the upper than the lower limb thus forming a fan which opens to the northwest. All parts of this fold participate and reveal an identical deformation plan: fold axes are nearly horizontal, cleavage dips southeast, lineation is in the cleavage plane normal to the fold axes, also dipping east. All formations including the volcanics participate.

Deformation axes have been determined at several hundred localities by systematic measurement of oöid distortions in Cambero–Ordovician oölites. The directions are shown in maps and diagrams.

Intensity of deformation varies greatly within the fold depending on (1) physical properties of materials (2) location within the fold and (3) geographical location.

Undeformed crystalline micropebbles and detrital carbonate grains within highly distorted oölites seem to indicate that deformation affected rather soft and pliable and maybe little consolidated rocks. Undistorted growth aprons on deformed oöids and crystallization of matrix are postkinematic and serve to date deformation and consolidation.

Approaching South Mountain from the west intensity grows gradually, is strongest in the lower limb, decreases toward the crest and the upper limb. Abrupt changes as would be expected in large-scale thrusting were not observed, the deformation seems to have been absorbed within a much wider complex.

Cleavage is invariably defined by the maximum (a) and mean (b) axis of distortion and not by a shear plane. This also points toward flowage as distinct from shearing of solids.

The fold is interpreted as a large "shear" fold as distinct from flexures. Deformation is thought to be due to laminar flow on subparallel planes. The presence of flow planes and the fact that oöids are extended at large angles to bedding show that stratigraphic thicknesses as now seen are not equivalent to depths of deposition. Calculations indicate that the latter amounted to less than one half of the present thickness.

Analysis of South Mountain fold requires reconstructions not usually applied in tectonic analysis. If deformation affected soft strata, exaggeration of thicknesses would go unnoticed but for painstaking structural observations, not commonly undertaken in stratigraphic research at present.

Careful microscopic investigation of the constituents of the oölites permits the dating of deformation, crystallization, consolidation, and, generally, the relation between diagenesis and deformation. Lateral shortening cannot be determined by straightening the strata into the horizontal if cleavage is present, but reconstruction becomes much more complicated in a "shear" fold. The author has attempted such a reconstruction using oöid distortion.

INTRODUCTION

PURPOSE OF STUDY

This study uses the measurable distortion of the oöids in oölitic limestones in quantitative determination of deformation, and the analysis is applied to South Mountain

in southern Pennsylvania and Maryland. The author suggests a method for systematic observation, sampling, measurement, and calculation. Maps have been constructed showing the distribution of deformation intensities and the direction of maximum cöid elongation in relation to regional structures. An analysis of the mutual relationships of well-defined structures like lineations, cleavages, bedding, folds, and fractures has been undertaken to determine angular relationships and sequence.

The cöid is only a means to an end, and its origin has been investigated only insofar as it is pertinent. It is most unfortunate that oöids are not more common and more widely distributed. They are ideal for quantitative determination of deformation unless silicification or dolomitization has rendered them useless.

The imperfect distribution of cöids and their restriction to definite layers and formations leaves the present study incomplete. However, as it is possible to reconstruct the geology of an area from scattered exposures it is also possible to determine deformation in spots and still obtain a fairly satisfactory and valid picture.

The study is thought to be only a beginning, and it is hoped that a systematic investigation of other areas and problems may improve the method considerably.

About 90 days were spent in the field in addition to mapping Washington County, Md., for the Maryland Geological Survey, and about 250 days were spent in the laboratory investigations. Due to war work and other interruptions, this report has been delayed several years. Financial resources and time were limited prohibiting further comparative investigation. The author feels however, that a stage has been reached at which a report is justified and useful.

The literature has been searched for an application of quantitative measurements of deformation to an area but I have found none. Measurements have been made at many points, by means of fossils, pebbles, cöids, spots, concretions, and other forms, but no systematic regional study seems to exist.

ACKNOWLEDGMENTS

The present investigation was made possible through a generous grant by the Geological Society of America from the Penrose Bequest.

The author has also received help and encouragement from many other sources. Richard H. Gault assisted in the observations and calculations and checked many of the measurements. He also provided the author with a list of minerals found in the slides. Frank M. Swartz provided samples from the central Appalachian area. Samples were given by H. R. Gault and L. B. Mather for comparison with undeformed cöolites. The preliminary results were presented to the New York Academy of Sciences, the Geological Society of Washington, and others. The author is grateful for stimulation and advice received during many discussions and from many individuals.

Edward Wisser critically read the paper, contributed most helpfully to the discussion, and called attention to numerous flaws.

The author is also grateful for many helpful suggestions by the editor.

HISTORICAL REVIEW

The history of quantitative investigation begins with an early phase of discovery and description but with little application. At that time cleavage was believed by many to be caused by magnetism or electricity, and mechanical deformation was emphatically denied. A second period began when Albert Heim published the results of some of his observations. Emphasis was on field work, description, illustration, and presentation of facts and much less on theoretical analysis. A third phase began with the introduction of microtectonic fabric study and analysis of the physical aspects of deformation. This approach has led to increased refinement and very much more detailed investigation. Statistical methods have been applied, and much microscopic work has been and is being done.

The first systematic effort to use distortion of known shapes in an interpretation of cleavage and an attempt to analyze movements and rock deformation were by British geologists of the middle of the last century.

J. Phillips pictured and described distorted fossils in 1843.

Sharpe in 1846 published on distortion of *Spirifer giganteus* and *Spirifer disjunctus*. A systematic investigation of many species seems to indicate that rocks showing cleavage have undergone:

> "1st A compression of their mass in a direction everywhere perpendicular to the planes of cleavage.
> "2nd An expansion of their mass along the planes of cleavage in the direction of a line at right angles to the line of incidence of the planes of bedding and cleavage; or in other words, in the direction of the dip of the cleavage.
> "No proof has been found that the rock has suffered any change in the direction of the strike of the cleavage planes. We must therefore presume that the masses of rock have not been altered in that direction."

H. C. Sorby (1853) prepared thin sections for the study of cleavage which he thought due to "some peculiarity of structure." He stresses the "great change of mechanical dimensions" which slate has suffered. Intensity of cleavage is closely linked with degree of change, and deformed green spots in slate serve as indication of distortion. In rocks without cleavage green spots are "almost perfect spheres," or are elongated in the plane of bedding. "Now, however, they are greatly compressed in a line perpendicular to cleavage, and somewhat elongated in the line of its dip."

Many careful measurements show axial ratios as recomputed in the present terminology: $a:b:c=1.6:1:.27$. This author concludes that a large condensation of the rock normal to cleavage has taken place. Sorby's theory precipitated considerable controversy and discussion.

The question was taken up again by Haughton (1856) who made numerous observations on the distortion of fossils. His analysis is detailed and he provided formulae for the calculation of distortion.

Haughton (1856, p. 410–411) proposed three laws: (1) If the trace of intersection of the plane of cleavage and plane of bedding be drawn, the greatest distortion or elongation of the fossils lying in the plane of bedding is parallel to this intersection. (2) The distortion of fossils produced by cleavage—estimated in a given direction, such as parallel to the intersection of the planes of cleavage and bedding—varies

with the angle between these planes, being greatest when the angle is greatest, and least when the angle is least. (3) The compression in a cleaved rock is greatest in a direction perpendicular to the planes of cleavage.

He then applies Cauchy's ellipsoid of distortion. The three ellipsoid axes are *a, b, c.* The intersection between bedding and cleavage is *y*, *z* is perpendicular to cleavage, and *y* is in the dip of cleavage normal to *x* and *z*.

Several examples show fossil distortion as related to the position of cleavage and bedding.

"The preceding Table [on p. 421] is, I believe, the first attempt to estimate numerically the amount of compression necessary to produce cleavage in rocks; and it is to be hoped that the attention of geological observers may in future be more directed to the observation of the relative position of the planes of cleavage and bedding, and of the distortion of the fossils; such observations, to be of any value, should be made in the field, by persons competent to judge of the shape of the fossil forms, and carefully instructed as to the precise points necessary to be observed.

"An opportunity of obtaining the information requisite for a perfect mechanical theory of cleavage is afforded by the means of observation possessed by the staff of the Geological Survey of Great Britain and Ireland. If the operation of such a survey were conducted with the science and skill necessary for carrying out such an important work, nothing would be wanting to complete the data requisite for the solution of many interesting problems in physical geology. But it is much to be feared, that so long as geologists remain in the half-educated condition with which they are at present contented, that such an amount of intelligent observation is not to be looked for; and that those who wish for satisfactory foundations of facts on which to build their theories, must even be content to take their hammers in their hands, and having strapped on their knapsacks, to seek in the field of nature the facts for themselves."

The first description of pebble elongation in America seems to be in Hitchcock and Hager's (1861, p. 29–50) report on the geology of Vermont. Influenced by the British School they observed metamorphic structures, cleavage, and distortion of pebbles at Vermont and Rhode Island localities. Conversion of the conglomerates into gneissic rocks presents a considerable problem, and the authors try to prove the now little-disputed fact of metamorphism and argue for plastic deformation as shown in the pebble elongation.

In 1875 Dufet published an article on the distortion of trilobites in schist.

Daubrée (1876) cites several examples of fossil distortion, particularly of extension of belemnites and tries to establish the relation between schistosity and deformation. He agrees with Sorby on mechanical deformation in contradistinction to magnetic forces.

A most comprehensive and fundamental contribution in Albert Hein's analysis of the mechanism of "Gebirgsbildung" (1878). Heim's analysis is based on field observation. Schistosity, stretching, bending, and deformation in general are described as seen in folds, elongated ammonites and belemnites and culminating in the formation of transversal cleavage. All particles are oriented in a plane normal to pressure, and the orientation of this plane is independent of bedding. Lineation in cleavage planes indicates the direction of escape.

Distorted cöids are mentioned (p. 60) from schistose portions of the Blegi iron cölite. Massive beds show only slightly elliptical or undeformed cöids, but in less competent beds they are intensely pressed and flattened. Undeformed magnetite octahedra show that the deformation took place prior to magnetite crystallization.

This seems to be the first discussion of cöid deformation.

Jannettaz (1884) pictures compressed ammonites and belemnites and has drawn

a block diagram (p. 225) showing three-dimensional deformation of a sphere into a triaxial ellipsoid. The three planes are the three principal planes of the isothermal ellipsoid. Experiments in a pressure box show that deformations can be reproduced and that the cleavage is oriented as in nature.

One of the most elegant and thorough investigations of deformed fossils is by Wettstein (1886) who used the fishes of the *glarnerschiefer* in Switzerland. The fishes are distorted in varying degrees and have therefore been thought to represent different species. Wettstein's primary purpose was to reconstruct the skeletons to an undeformed shape and then by comparison eliminate many unnecessary new species. The work was done largely in museums.

Wettstein devised a very clever computation method and determined many hundreds of distortions. Two directions are considered: one within the bedding plane, since most of the skeletons are flat in that plane, and the flattening of the spines perpendicular to bedding. Important are: the ratio of body width and length, the angle between spinal column and spines, and the shape of the vertebra. The form of the fossil depends on its position with respect to the direction of stretching. The author calculated the angular change between two lines that were mutually perpendicular before deformation.

The calculation of deformation and reconstruction of the original shapes shows the distortion within the bedding plane in which the fish came to rest, but the position of that plane in the deformation ellipsoid does not become clear. If the angle between cleavage and bedding had been given in each instance, it would have been possible to construct the ellipsoid.

Hans Reusch (1888) pictures deformed pebbles and fossils in the description of Bømmeløen and Karmøen, two islands south of Bergen, Norway. The deformation of that area is described in a beautiful study.

The first mention of cölite deformation in the title of a paper is in Chapman's (1893) brief description of sheared limestone from Ilfracombe. Plate V shows several types of strongly deformed cöids. "Solitary quartz and dolomite crystals" are obviously later than deformation of cöids. Much silification has occurred. The oöids are about 1.mm across. Shearing extended the cöids to twice their thickness, and some grains reach ratios of 5:1. Chapman's Figure 4 shows grains which are pulled out to a ratio of 10:1.

Elongated cölites in Thuringia are described by Loretz (1882) and Sieburg (1909) as oriented with their longest and mean axis in the cleavage plane and with the shortest axis normal to it. Well-stretched pebbles are mentioned by Peach (1912) and many of the other workers in Scotland, but a systematic study has not been undertaken.

V. M. Goldschmidt (1916) described the most intensely deformed conglomerate below the overthrust at Bygdin, Norway, which has recently again been analyzed in more detail by Strand (1945). The pebbles are elongated to a ratio of 1:1.5:80.

Greenly (1919) mentions pebble and fossil distortion from Anglesey in a very detailed and comprehensive report on that region.

Albert Heim's analysis of triaxial deformation is well known. Based on a large store of observations it is valuable, though some interpretations may have to be

modified. Three deformation axes are used: *a* parallel to fold axes (*b* of Sander) "the axis of least change or of unchanged dimension; axis of least deformation;" *c* parallel to cleavage and down-dip (*a* of Sander) "axis of maximum stretching and escape;" and *b* normal to the other two, "the axis of maximum shortening normal to cleavage" (*c* of Sander).

Deformation of fossils, pebbles, and oöids is described, and axial ratios of 1:1:2 to 1:1:5 have been measured. Flowage ("deformation without fracture") is emphasized (p. 92) and Foraminifera, belemnites, and ammonites have been observed in great numbers. Extension up to 10 or 12 times the original diameter seems to be common within the intensely deformed portions. The author repeatedly stresses the thought that all deformed rocks were consolidated rocks before folding.

Oölite axial ratios in the chamosite oölite of the Windgälle are $b:c=1:6$ to 1:15.

Pebble distortion is also well known from the Canadian Shield. Quirke and Collins (1930) have described pebbles of the Bruce conglomerate as 8 to 10 inches long and 3 to 4 inches thick. A recent study by Pettijohn (1934) has attacked the problem from a stratigraphic and sedimentary angle. Normal or undeformed pebbles of the Abram series show ratios of 1:1 to 1:5, depending on the original shape. In the schistose conglomerate the ratio becomes 1:4 to over 1:7. Unfortunately the deformation is given only in two dimensions, and field orientations which would prove valuable are lacking.

With the introduction of mathematical analysis by G. F. Becker (1893) and the later development of fabric analyses by Sander (particularly 1930) and Schmidt (1932) emphasis shifted gradually to determinations of mineral orientations, statistical methods, and more detailed microscopic work. There was an accompanying shift from the more geological emphasis of field observation to petrographic analysis. Investigations have become more intensive and more precise.

Typical of this phase are the studies by Drescher (1932) and Scheumann (1936) of a Silesian quartzite containing date-shaped bodies resembling stretched pebbles. Fabric examination does not reveal whether these bodies are pebbles or concretions, but Scheumann has sound geological grounds for believing them to be pebbles. The controversy seems trivial but is typical in the difference of approach of the two authors.

Sander (1930, e.g.) and Schmidt (1932) discuss three-dimensional deformation at some length. Albert Heim (1921) on the other hand illustrates it by means of innumerable field observations. All three authors stress the third dimension which is frequently overlooked or neglected.

A rather typical example of a modern analysis of three-dimensional deformation is by L. Rüger (1935) who studied pebbles in a gneiss conglomerate from the Erzgebirge in Saxony. Emphasis is on mineral orientation and fabric symmetry. Measurements include mica and quartz orientations in matrix and pebbles. Quartz is postdeformational, and the diagrams show the maximum pebble axis as a girdle axis. It is strange and somewhat significant that pebble dimensions are omitted in a study which includes the measurements of 45,640 grain orientations. Obviously the author is painstakingly careful, patient, and intent on detail. It would have been

of considerable interest to know the average pebble size and the distribution of pebble size in relation to deformation and its regional variation.

A deformed conglomerate in the Black Hills area is described by Runner (1934) from the Estes conglomerate. Pebbles are distorted into triaxial ellipsoids whose maximum and intermediate axes lie in the flow cleavage plane and parallel to the axial plane of folds. The long axis parallels the pitch of the folds (p. 359).

The same author describes concretions that have become triaxial ellipsoids. Average size of the concretions is that of watermelons, and the axial ratio is 3:2 of the long to the shortest axis. The long axes are mutually parallel over a considerable area and pitch at low angles southwest of the fold axes.

"Within the ellipsoids, however, the plane and the linear flow cleavages frequently intersect the plane of the major and intermediate axes of the ellipsoids at angles of as much as 20°, indicating that later recrystallization under differential pressure took place under stress applied in different directions from those that shaped the ellipsoids."

Fairbairn (1936) describes elongated pebbles parallel to steep fold axes, and elongation is discussed in terms of two phases of deformation which are ruled out. The author accepts Sander's concept of rotational deformation accompanied by elongation parallel with the axis of rotation.

A very thorough and detailed petrologic study of Silesian conglomerates has been carried out by Scheumann (1936).

The Scandinavian highland conglomerates have recently attracted more attention in three studies by Strand (1938; 1945) and Kvale (1945). Deformed pebbles in Nordre Etnedal are mentioned in the report on that quadrangle. Dimensions are given as 45:10:3, 20:9:2, 32:11:7, and 24:7:3 centimeters. The same author has recently studied the Bygdin conglomerate described by Goldschmidt in 1916. On the basis of a fabric analysis the author concludes that the pebble elongation is in the direction of forward movement on the Caledonian overthrust. Kvale (1945) describes stretched conglomerate in the Bergsdalen quadrangle east of Bergen. In most places pebbles are shaped like canes and pencils 1 by 3 by 100 cm in size. Fabric diagrams of quartz and mica show girdles around the maximum axis, but field evidence shows that maximum movements must have been parallel to the maximum extension of pebbles. The author tries to co-ordinate the conventional interpretation with his findings but finds this difficult.

A detailed and very competent paper by Mehnert (1939) deals with the deformation of a "Meta conglomerate" in Saxony. A petrographic description precedes the mechanical analysis (p. 250). Primary shape of pebbles has been studied but plays only a small part. The pebbles approximate triaxial ellipsoids. Maximum axis a and mean axis b are in the cleavage plane, the shortest axis is normal to it. The ratios $u\frac{(b)}{c}$, $v\frac{(a)}{c}$, and $w\frac{(b)}{a}$ can be determined. Pebble shape depends on intensity of deformation and the material. Two facts become apparent: deformation varies in different horizons of the geologic section, and the graywacke pebbles are more deformed than quartz pebbles. Ratios (b:c) are as follows: (1) quartz 1:1–2:1; (2)

coarse quartzite 8:1; (3) dense graywacke 10:1–12:1; (4) schistose graywacke and shales 18:1.

Pebble ratios in the Mt. Cube area, New Hampshire, are cited by Hadley (1942) as 1:2:4 and 1:3:8. "The shortest axis [is] always normal to the bedding and schistosity."

The present author has repeatedly called attention to systematic measurements of oölite deformation and their application (Cloos and Hietanen, 1941; E. Cloos, 1942; 1943; 1945). These preliminary papers were presented because the present report has been unduly delayed.

The wide horizontal distribution of oölitic limestones in the Paleozoic of the Appalachians renders determinations of deformation of a larger area possible. The author has studied the area west of South Mountain between the Susquehanna and Potomac rivers, but extension of the study into the areas north and southward seems to be very promising.

This review of the literature includes only some of the major papers on the distortion of known shapes and quantitative estimates of three-dimensional deformation. Obviously pebble deformations are most favored and have attracted wide attention, whereas cölites have been neglected. Techniques have greatly improved in recent years, and it seems appropriate to attempt a regional analysis based on observations at many points, systematically scattered and chosen with respect to their position n the structural province.

DEFINITION OF OÖLITES AND SPHERULITES

Following Bucher (1918, p. 593, footnote): "A rock is called 'oölitic' or an 'oölite' if it contains or consists of small grains or units of dominantly concentric structure. A rock is called 'spherulitic' (but not a spherulite) if it contains or consists of small grains or units of dominantly radial crystalline structure. An individual grain of a spherulitic rock is called a 'spherulite'."

In this sense an oölite and spherulite are more or less incompatible. Twenhofel (1926, p. 533) states: "Oölites are small particles of elliptical or spherical shapes with concentrically laminated or radiate structure."

In a later edition, Twenhofel (1932, p. 757) defines oölites as

> "small rock particles of elliptical or spherical shape with concentrically laminated structure . . . particles of dimensions similar to oölites and pisolites but with radiate and not concentric structure are designated spherulites. It is to be noted, however, that this latter term has also been applied to spherical aggregates without either radiate or concentric structure. Many oölites and pisolites have radiate structure in some or all of the laminations."

According to Dana (1932, p. 329)

> "spherulites (are) aggregates spherical in form and radiated or concentric in structure; . . . they commonly exhibit a dark cross in the microscope between crossed nicols; further, this cross, as the section is revolved on the stage, though actually stationary, seems to rotate backward."

According to Dana's definition oölites are spherulites if they exhibit the "dark cross" under the microscope. Merely round spherical bodies like pebbles, single minerals, mud pellets with concentric layers, are not spherulites.

Inasmuch as the "dark cross" and the radial structure can be seen only under the

microscope and as the present investigation is based on microscopic work, the presence of the dark cross has been used to distinguish spherulites. As used here all bodies showing radial growth from a center have been classified as spherulites. All spherulites are here also oöids, but not all oöids are spherulitic or spherulites. Included in the oöids are also mud pellets, but excluded are all spherical detrital bodies like quartz grains, carbonate grains, or clusters which seem to be rounded by rolling. Thus, oöids are small spherical or ellipsoidal bodies due to growth from a center or with respect to a center. They may be spherulitic, that is radially arranged, and show a dark cross under crossed nicols or they may consist of concentric layers without spherulitic properties. The rock that consists of cöids is an cölite.

The majority of the oöids investigated show both dark crosses and concentric layers. Some oöids are spherulitic only in layers or in the center. Seventeen of 186 specimens are entirely free of spherulites and consist only of mud pellets with concentric structures.

DESIGNATION OF CO-ORDINATES AND SYMBOLS

The following designations have been used: A = maximum strain—ellipsoid axis; B = mean axis; C = smallest axis (Sander, 1930, p. 52). Co-ordinates a, b, c, according to Sander and many other workers (E. Cloos, 1946, p. 5) are arranged so that b parallels the fold axis, a is the direction of tectonic transport, and c is normal to the ab plane. If b is an axis of rotation it becomes B (Sander, 1930, p. 51; Knopf and Ingerson, 1938, p. 46). The maximum, mean, and minimum half axes of the deformed oöids are a, b, and c. Prior to deformation a = b = c, the oöids are spheres. l is lineation (E. Cloos, 1946, p. 4).

GENERAL GEOLOGY OF THE AREA

The Great Valley west of Blue Ridge between the Potomac and Susquehanna rivers has been systematically searched for deformed oöids (Fig. 1). East of the Blue Ridge are the triassic belt and the Piedmont crystallines.

In Maryland Blue Ridge consists of South Mountain and Catoctin Mountain. Between the two is Middletown Valley. To the north and northeast only one range continues as Blue Ridge which plunges northeast and disappears south of Carlisle.

South Mountain and Catoctin Mountain are the western and eastern limbs of a large overturned fold here called the South Mountain fold.

The core of the fold consists of a complex of metavolcanic rocks named Catoctin belt by Keith (1893) and generally metamorphosed volcanics by Jonas and Stose (1932). Above this series are the lower Paleozoic rocks of the Appalachians as shown in Table 1.

Table 1 is generalized and not very satisfactory in the field.

Most of the oölites are in the Conococheague, but they occur also in the Stones River, Chambersburg, and Beekmantown above and the Elbrook, Waynesboro, and Tomstown below.

South Mountain is a curved anticlinorium beginning south of Carlisle where lower Paleozoic and underlying rocks emerge in a number of folds which plunge northeast.

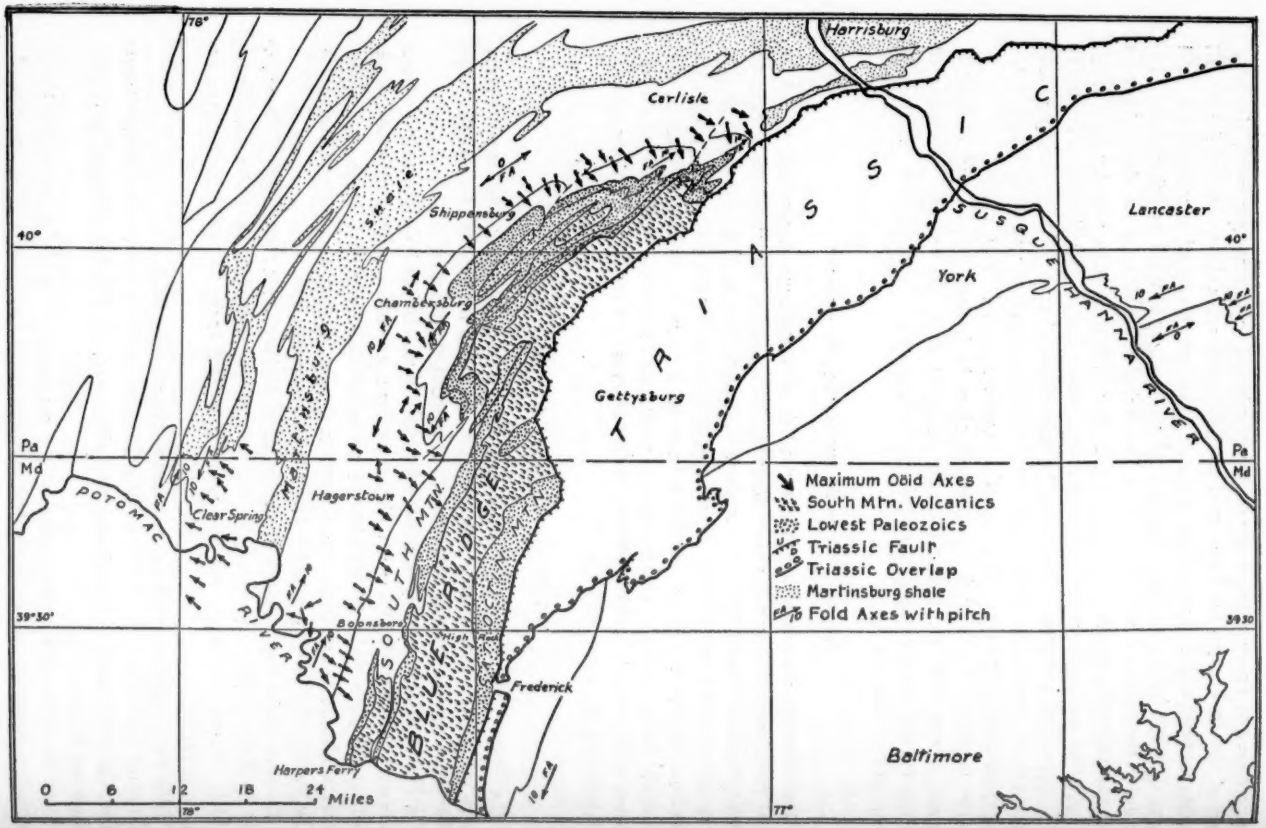


FIGURE 1.—*Index map of Appalachian Valley*
Localities, maximum oöid axes, and general trend of structural units.

The axes here strike northeast but cross the Potomac River striking almost north-south. This arcuation is shown in Figure 1 and Plates 9–11 and is common to all Appalachian folds in this section.

TABLE 1.—*Geologic column of the area*
(After Geological map of Maryland, 1933)

	ORDOVICIAN
Juniata	Red sandstone and shales; 400 feet
Martinsburg	Black shales overlain by yellowish-green sandy strata; 2100 feet
Chambersburg	Thin-bedded limestone with argillaceous partings; 500 ± feet
*Stones River	Pure limestone with cauliflower cherts and edgewise conglomerates; 1100 feet
*Beekmantown	Pure limestone interbedded with impure finely laminated beds; 2000 ± feet
	CAMBRIAN
*Conococheague	Thick-bedded siliceous banded limestones with "edgewise conglomerates"; 1500 feet
*Elbrook	Light-blue and gray shaly limestones; 3000 feet
*Waynesboro	Reddish to purple calcareous sandstones and shales; 1000 feet
*Tomstown	Shaly dolomitic marble with thin shales; 1000 ± feet
Antietam	Coarse-grained white to bluish sandstones and quartzite; 800 feet
Harpers	Bluish-gray sandy slates and schists; 1200 feet
Weverton	Massive white and purple sandstones and quartzite; 800 feet
Loudon	Dark slates, sandstones, shales and marbles; 500 feet
	UNCONFORMITY
	PRE-CAMBRIAN
Catoctin schist, greenstone, aporhyolite, metabasalt, *etc.*	

Thicknesses are not measured but largely estimated.
* Oölite beds occur in this formation.

FIGURE 1.—*Index map of Appalachian Valley*
Localities, maximum cold axes, and general trend of structural units.

The western and lower limb is generally steep and, as seen in Figures 2 and 20, is overturned to the west. In the crest of South Mountain, Maryland, east of Boonsboro and many other localities, a systematic search of crossbedding in the quartzites (by B. L. Mather) has shown that at some places these beds are overturned and now dip very gently east. (*See* Cloos and Hietanen, 1941.) Some of the lower Paleozoic formations are locally pinched out. Axial-plane cleavage dips east at angles of 20°–50°, generally more gently in the lower limb. Catoctin Mountain is in the upper limb of this large anticlinorium and here, at High Rock, and farther north Cambrian Strata are almost horizontal.

South Mountain fold is felt far out into the Hagerstown Valley. Cleavage dips gently east and southeast in the Cambro-Ordovician of the western limb, and beds are largely vertical or steep. Figure 2 is a cross section showing an interpretation of the western slope east of Hagerstown. The sequence in the lower limb of the fold is normal. As will be shown the overriding overturned fold has affected the entire lower limb and all formations contained therein. The amount of deformation of the lower limb is largely shown in the deformation of the cöids.

The limestones of the Hagerstown-Shippensburg-Carlisle valley have been thrown into a series of shallow folds with steep axial planes and almost horizontal fold axes. The lowest point of this syncline is reached in the valley of Conococheague Creek west of Hagerstown where Martinsburg shale is exposed in a steep syncline probably emphasized by strike faults.

In Maryland the west side of the valley is again in the lower Conococheague and Elbrook limestones which are faulted against Devonian and Silurian of the northern end of Massanutten Mountain.

METHOD OF INVESTIGATION

GENERAL REMARKS

The average diameter of the cöids is below one millimeter and ranges from 0.33 mm to 1.2 mm. Only in one layer southwest of Clearspring have cöids of over 1 cm diameter been observed. Wherever deformation is intense, oölites cannot be recognized but either by hand lens or binocular and many specimens were collected which are not oölites but turned out to be fine-grained fragmental limestones.

Recognition of directions of deformation is difficult if exposures are not three-dimensional and ratios small. Thin sections made in wrong directions may be misleading, and one of the most difficult steps is the determination of maximum and minimum directions in odd-shaped specimens or exposures.

Great care and thus a good deal of time has to be invested if accuracy is to be attained. A mistake in any one of the stages will never be cancelled out. Careful check and recheck by another investigator and plotting into three-dimensional diagrams prevents errors, and the author feels confident that the accuracy here attained is satisfactory.

H. R. Gault has recalculated 90 per cent of all figures used here and remeasured many of the slides, checked orientations repeatedly, and in general eliminated many errors.

Specimens have been collected at 241 localities. Two hundred and twenty-seven of these are oriented. Four hundred and four thin sections have been examined and measured. Fifty-five localities furnished nonoölitic limestone, deformation beyond measuring, or material which could not be used. Reliable measurements are available for 186 localities, and these have been plotted on the maps (Pls. 9–11).

All but two samples are limestones with varying amounts of dolomite, quartz, carbonaceous matter, and very fine muddy shale. Many are fossiliferous, and all contain quartz. Some hematite, fluorite, pyrite, and chert was found in small

FIGURE 2.—*Generalized cross section*

Across South Mountain, Middletown Valley, and Catoctin Mountain, showing overturned anticlinae with gently-dipping lower limb. Cleavage dips east in all rocks and transects formational boundaries far into Hagerstown Valley.

amounts. Two examples of siliceous oölite are interpreted as chert replacements The author has searched for good exposures and then searched the exposures for oölites. A good horizon may be followed and investigated for good measurements at even intervals.

Deformed oöids serve the same purpose whether they are in the Beekmantown limestone, the Conococheague, or the Tomstown. However, certain horizons are more oölitic than others and were thus more frequently encountered. The maps (Pls. 9–11) are, therefore, not geological maps even if the distribution of localities reflects the regional arrangement of formations and especially of the Conococheague limestone.

In view of the intricacy of the observations and the smallness of the average oöid, it was necessary to verify field observations by thin-section study. A microscope was, therefore, taken into the field, and thin sections made as soon as practicable. The sections were then measured and calculated, and the results applied in further collecting and checked in the field. In this manner, field and laboratory work alternated, revisions and corrections were made and much unnecessary mileage was eliminated, and the search directed to the most essential points.

First a rather loose net of scattered observations was spread over a larger area. Fixed points were established, and then observations filled in wherever necessary or desirable. Where orientations and ratios of deformed oöids are constant over many miles, gaps were left in favor of more intricate areas. In this manner the number of thin sections was reduced to a useful minimum, and they are now placed where they provide most useful information.

One hundred and twelve samples show spherulitic oöids with typical radial growth and extinction cross under crossed nicols. Eighty-four samples also contain ample muddy or shale pellets or lumps, or are without spherulites. Detrital dolomite pebbles occur in 28 samples some of which are not measurable because of lack of spherulites or pellets. Good bedding can be seen in 34 samples. Euhedral quartz is common in 26 specimens and zonal growth of quartz can be seen in 20 specimens.

FIELD WORK

Prior to the study of oölite deformation the author had completed geological mapping of Washington County (E. Cloos, 1942) and was therefore familiar with the rock types, oölite locations, and the terrane in general. The area was then extended northward across the Mercersburg-Chambersburg quadrangles (Stose, 1909) and northeastward to the east end of the South Mountain fold southeast of Carlisle.

A complete structural inventory at every locality is indispensable. Bedding, cleavages, fold axes, intersections of bedding and cleavage or cleavages, lineations in bedding and cleavage planes were measured and plotted in the field. Drawings, block diagrams, and descriptions are of great assistance in the evaluation of the measurements later. Errors in later stages may be eliminated if the locality is well known and the accuracy of orientation can easily be checked against field measurements.

Joints and fractures of all kinds were measured wherever possible.

SPECIMEN SELECTION AND ORIENTATION

Since oöids are hard to see in fresh exposures or freshly trimmed specimens, field observations are mostly from slightly weathered exposures which are whitish gray, bluish gray, or otherwise bleached even on almost black limestones or dolomites.

Selected specimens are best loosened from solid rock and then refitted because they frequently break in trimming across marked orientations, and a new specimen has to be taken. In refitting, all dust and small pieces must be blown away from the fracture to assure perfect relocation. The piece can easily be held in place by a strip of adhesive tape which permits all following operations without continuous falling off of the specimen.

The sample should show two surfaces normal to each other to permit determination of deformation under a binocular and thus enable the investigator to choose the proper directions for sawing. Strike and dip of the smoothest and largest even surface are then measured, and the directions scratched on that surface with a sharp-pointed tool, and also marked with adhesive tape. Directions are noted, and in order to avoid later confusion the surface is also plotted in its proper location with north at the top of the page. An arrow for the strike with attached dip sign will exclude all other possibilities like east or west dip or confusion of top and bottom of specimen.

White bases were painted on the specimen with quick-drying paint, and orientations marked with india ink. A coat of shellac protects this permanent label against damage during shipping, handling, and grinding. All pertinent data were entered in a card catalogue. The same data were later also entered in a book, and the records kept separate as insurance against loss.

A rough determination of the future saw cuts in the field is most serviceable, particularly if these are then checked against lineation, cleavage, or bedding which may be only faintly visible in the sample but excellent in the large exposure. It is very much easier and also more accurate to mark a line on a specimen in the field than to re- orient the specimen in the laboratory and to determine the cuts there.

The author used an average of one hour to an hour and a half for one location, including all measurements, orientation, labeling of specimens and notes. A field day with 10 specimens collected was a good one and unfortunately, there were days with none.

As a rule specimens are comparatively large and should not weigh less than half or three-quarters of a pound. In taking samples, one should bear in mind that sawing will be necessary, and odd-shaped pieces should be avoided since they cannot be clamped readily for sawing. Sawing is easiest and also cheapest across specimens which are bounded by two roughly parallel planes. Cuts parallel to thin slabs, for instance parallel cleavage, are difficult to obtain accurately.

DETERMINATION OF CUTS

Proper orientation of thin sections with respect to the axes of deformation is one of the critical steps in the investigation, particularly if distinct lineation is not visible in the field or if exposures are not three-dimensional.

Deformed oöids are triaxial ellipsoids, and two thin sections perpendicular to each

other may contain the three axes if properly oriented. They may, however, also contain three differing axes which are not the principal ones, and nothing in the thin sections indicates at what angle to the principal axes the section might have been cut.

In the area here analyzed, orientation is rather easy where cleavage is obvious. There should be one section perpendicular to cleavage, to the intersection of cleavage and bedding, and one parallel to cleavage and the intersection. One section should always contain visible lineation, and one the fold axis. Wherever cleavage is not visible a section parallel to the axial plane of the fold and one perpendicular to it and the fold axis is likely to include the principal axes of the ellipsoid.

It may become necessary to try several sections, and in such cases three or more sections are essential.

If two sections are made, one for instance containing the longest and shortest axes and a second one the longest and mean axes, a third one perpendicular to the two others will provide an excellent control and should contain the shortest and mean axes. In calculating ratios and the radius or diameter of the original sphere, the combination of either two sections should furnish the same result. Even small deviations from the principal axes may introduce large errors if the ratios are high and the maximum axis is large.

In the present investigation, the author observed a remarkable regularity of orientation along the entire western slope of South Mountain. Maximum elongation of oöids parallels lineation and is in the steepest dip of cleavage. Since most fold axes are nearly horizontal, a vertical cut perpendicular to cleavage and fold axes furnished the principal axes of deformation. In the less deformed western area where structures are less distinct, cuts were oriented in the same manner unless elongations in other directions were visible in the field. Wherever calculations disagreed, additional cuts were made.

MICROSCOPIC STUDY

Microscopic investigation includes a study of the mineral content of each slide, and measurement of oöid dimensions.

The mineralogical and petrographical study was done largely by H. R. Gault, who listed all minerals present in each slide and noted their textural relations and peculiarities.

The dimensions of the oöids were measured with a one-tenth millimeter grid ocular which greatly facilitates measurements because two co-ordinates are always given, and readings in the horizontal and vertical are quickly made. The slide was placed on a mechanical stage, and the sections covered systematically.

It is advisable to draw the slide and its orientation arrow at the top of each sheet on which measurements are noted and next to the arrow to note the degrees read on the microscope stage referring to the zero position in reference to which degrees are read. The dimensions can then be read north-south and east-west whereby it is best to always read the longest dimension either one way or the other in order to avoid confusion of notes later. An average maximum orientation can be read with low magni-

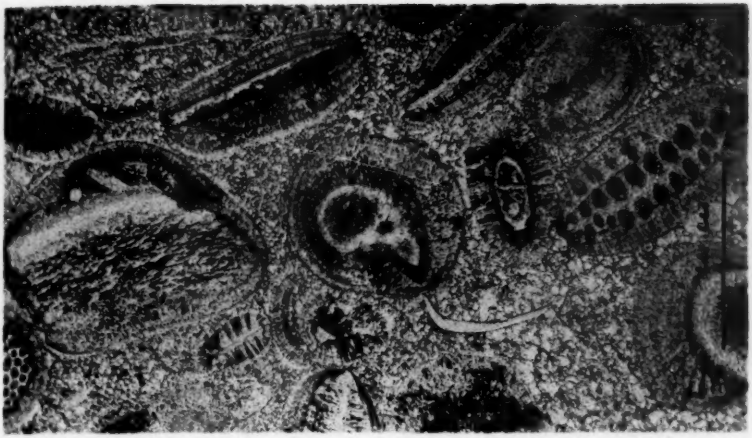


FIGURE 1. FOSSIL FRAGMENTS PARTLY COVERED WITH OÖIDS WHICH TEND TO FORM SPHERICAL BODIES BY RADIAL GROWTH
Loc. 449, Rose Hill, Md. Lower McKenzie, 9 to 10 feet above *Declarkei* zone. Sample by F. M. Swartz. Photomicrograph.

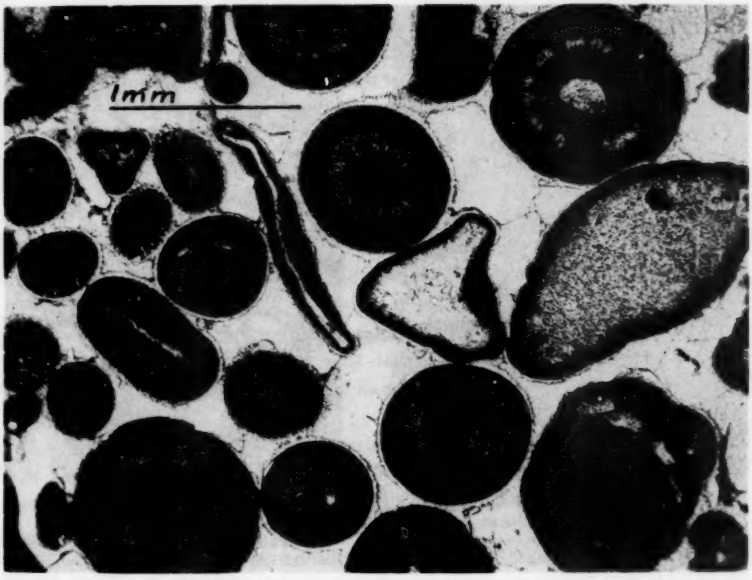


FIGURE 2. UNDEFORMED OIL-BEARING MCKLUSKY OÖLITE
Clay City, Ill. Specimen by Pure Oil Co. Undeformed oöids are surrounded by crystalline aprons. White: pore space.

UNDEFORMED OÖLITES

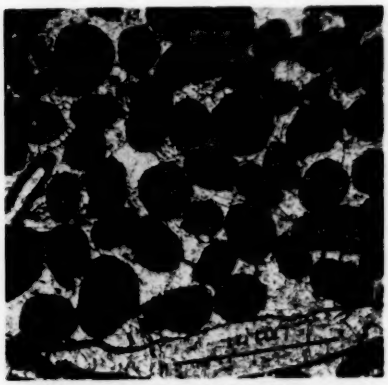


FIGURE 1. UNDEFORMED MUD PELLETS IN CRYSTALLINE MATRIX
Mille Roches, Ontario. Specimen by B. L. Mather. Photomicrograph.

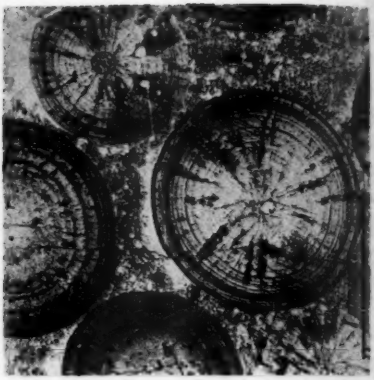


FIGURE 2. CHERT OÖLITE WITH RADIAL GROWTH AND CONCENTRIC RINGS
The right oöid is cut through center, the left oöid above center. Loc. 254 A, north of McConnelsburg, quarry north of road cross. Needmore quadrangle, Pa. Photomicrograph.

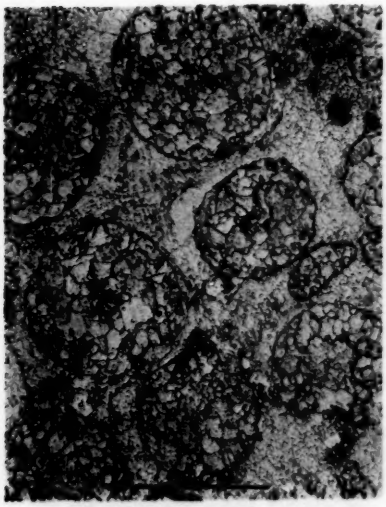


FIGURE 3. PEBBLES OF CRYSTALLINE AGGREGATE, UNDEFORMED
Loc. 278, east of Balls, Hagerstown quadrangle. Photomicrograph.

FIGURE 4. FOSSILIFEROUS BEEKMANTOWN LIMESTONE
With mud pellets, oöids, fragments, and rounded particles in crystalline matrix. Loc. 252, north of McConnelsburg, Pa. Photomicrograph.

PRIMARY DIFFERENCES IN OÖLITES

fication, thus providing a value which can then be checked against the measured average.

At first 100 readings were made per slide, but it was later found that 35 readings provide a value close to the average obtained from 100 measurements especially if orientation is distinct. Only few slides show no orientation.

Most oöids are sharply limited either by shells, coloration, or crystal boundaries, but frequently some new crystals have grown in the direction of maximum deformation thus increasing the ratio considerably. It seems reasonable to limit measurements to the actually deformed oöid and not to include secondary growth and enlargement. Calculations outlined below are based on deformation without change of volume. Secondary growth, however, increases the volume, and it would be difficult to include the increase in a determination of the size of the original sphere and its distortion.

In listing the measurements, the author first read the direction of maximum extension and then the minimum. The columns were then added mechanically and divided by the number of readings.

COMPUTATIONS

Oöids can be assumed to have been originally very nearly spherical bodies. Deviations can be seen in many slides as due to primary irregularities as, for instance, the shape of centers, irregular growth, or close packing. Such shapes are readily recognized and have not been used (Pls. 1, 2). In more than 400 slides there is no case in which primary eccentricity parallels a tectonic direction. Slight eccentricity which is not due to deformation remains unoriented. Elongation due to deformation can easily be detected because of uniform orientation (Pls. 4, 5, 6).

If the diameters of nonspherical undeformed oöids were plotted in a co-ordinate system, a sphere would result due to the random orientation of the eccentricity. This sphere can be used because random orientation has been changed to tectonic orientation in all grains of one specimen or location.

Tectonic orientations are obvious on the maps and illustrations, and deformation has more than doubled diameters. Primary eccentricity may introduce errors of 10 per cent, which carries little weight in deformations exceeding 100 per cent. The sensitivity of orientations even in the lowest deformations and the regional regularity seems sufficient guarantee that errors due to assumed sphericity of oöids would not alter the final result.

Fluctuation of orientation has been plotted against deformation ratio in Figure 3 for 144 slides. The range indicates the degree of parallelism of the longest dimension as measured by turning the microscope stage. The ratio is a/c. Perfectly spherical oöids should have the ratio 1, and it is clear that there are almost no spherical oöids represented. The range is reduced as ratio increases, but no slide shows less than 10° of fluctuation. At a ratio of 2:1 the long axis fluctuates still 50°, or 25° from the average.

Such fluctuations are well known in the orientation of mica grains in schists where only relatively few grains parallel the schistosity.

Figure 1 of Plate 4 shows intense and even alignment, a ratio of 1.4 and fluctuation of 25°. The ratio of Figure 1 of Plate 6 is 3 and fluctuation 20°, and in Figure 2 of Plate 6, the ratio is 2 and fluctuation also 20°. The slightly elliptical oöids in Figure 2 of Plate 1 fluctuate 180°, or 90° on either side of the average, and the ratio is 1.2. The four points are marked in Figure 2 by circles.

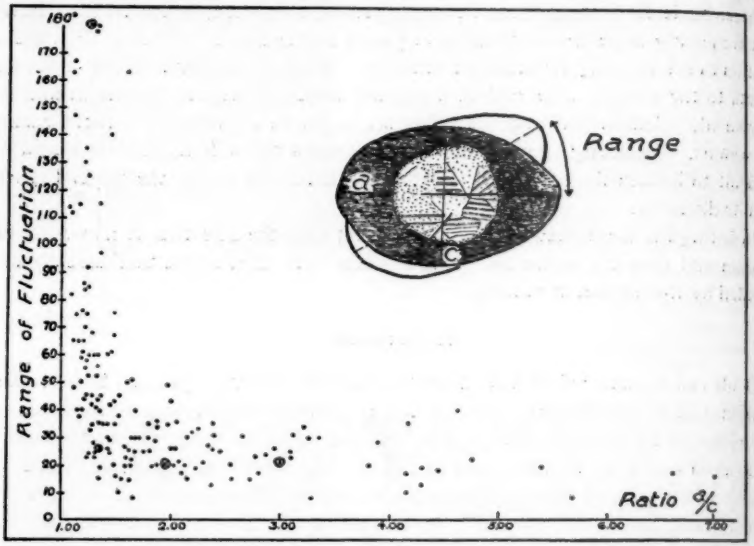


FIGURE 3.—*Range of fluctuation of orientation in relation to deformation ratio*

From the above it seems evident that eccentricity becomes significant only if the longest axes are oriented.

In the following procedure, a primary sphere was assumed as the original shape, and the deformation has been calculated with the diameter of the sphere as reference unit.

Two thin sections perpendicular to each other and containing the three semi-axes of the present ellipsoid a, b, and c permit calculation of the radius of the original sphere from which the ellipsoid has been derived provided that the volume has not changed. The volume of the sphere equals that of the ellipsoid:

$$\frac{4}{3}\pi r^3 = \frac{4}{3}\pi a.b.c.$$

$$r = \sqrt[3]{a.b.c.}$$

If, for example, the values measured at locality 300, northeast of Sharpsburg, Maryland, are used, the calculation is as follows:

2a = maximum diameter = 8.45, a = 4.23
2b = mean diameter = 6.74, b = 3.37
2c = minimum diameter = 5.06, c = 2.53
r = 4.23 × 3.37 × 2.53 = 3.3, d = 6.6

The components of deformation are, therefore:

$$2a = +1.85, \qquad 2b = +0.14, \qquad 2c = -1.54$$

In references to the original sphere the maximum extension in a is:

$$\frac{1.85 \times 100}{6.60} = 28\%$$

The extension in b is:

$$\frac{0.14 \times 100}{6.6} = 2.1\%$$

and the reduction of the c axis:

$$\frac{-1.54 \times 100}{6.6} = -23\%$$

One hundred twenty four specimens have been sawed in two directions, and all three components were determined. The average value of b is below 8 per cent. At 22 localities it is zero, and at some localities where maximum elongation is in b and not a, deformation reaches 30 per cent. b varies with the accuracy of the measurements of a and c, and where deformation is strong, the ends of oöids are drawn out, torn off, and frequently damaged, thus making precise measurements impossible and at the same time preventing accurate measurements of the two other dimensions. In all such slides b will be positive, and if a is much longer than can be measured, the value for b will be large. Wherever recrystallization has taken place as for instance in Figure 1 of Plate 5, a becomes too large and b becomes negative.

The most difficult direction to measure accurately is a, and its computation decides the fate of the other two axes.

An abbreviated method where only one section in ac is cut can be used occasionally and the calculations are made with the assumption that b = 0. Thus the deformation ellipsoid becomes an ellipse (*see* Nadai, 1931, p. 294), and the unit sphere has the radius b. Calculation is much simplified, and the results are also reliable. Where b is large but not measured, values for a and c become impossible and the second sections must be cut later.

If extension in b equals 0, the semi-axis is 1 + 0. Thus:

$$r^2 = ac \qquad \text{or}$$
$$r = \sqrt{ac}$$

For instance in locality 204 only one section has been cut in the ac plane. 2a = 35.5, 2c = 6.7, thus:

$$r = \sqrt[3]{17.7 \times 3.35} = \sqrt[3]{159.295} = 7.69$$

The diameter of the original sphere is 15.38. The increase in the direction of a is thus 20.12, the decrease in c is 8.68.

The extension of a in per cent amounts to:

$$\frac{20.12 \times 100}{15.38} = 130.8 \text{ or } 131\% \text{ of the diameter of the unit sphere.}$$

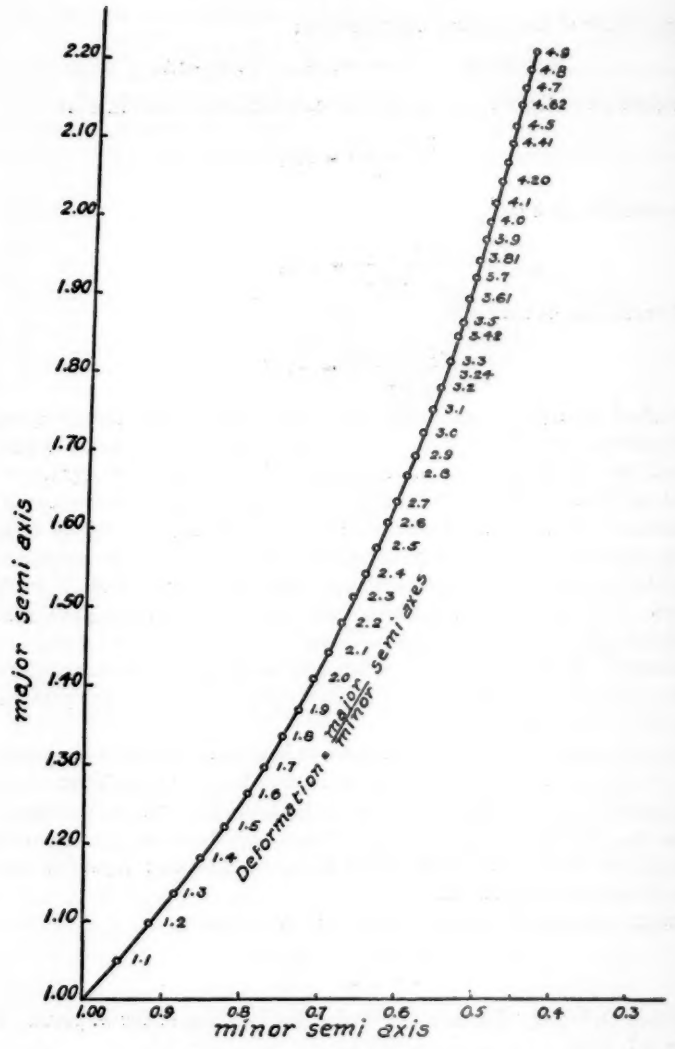


FIGURE 4.—*Plane strain with constant volume*

Curve shows major semi axes corresponding to minor semi axes, deformed from a circle with unit radius. Computed from Nadai 1931, p. 249 (2).

In order to reduce calculation, the ratio $\frac{a}{c}$ has been plotted into a curve from which the semi-axes and the extension can be read. The curve has been constructed by Edward Wisser and published here by his permission for the readers' convenience (Fig. 4).

One of the most important applications of the measurements of deformation is the increase or decrease of stratigraphic thicknesses in certain areas (E. Cloos, 1942). It is, therefore, necessary to calculate the components of deformation in relation to bedding. If a is perpendicular to bedding, the extension of a means increase of thickness by its full amount. If the angle becomes smaller, the component is reduced with the size of that angle.

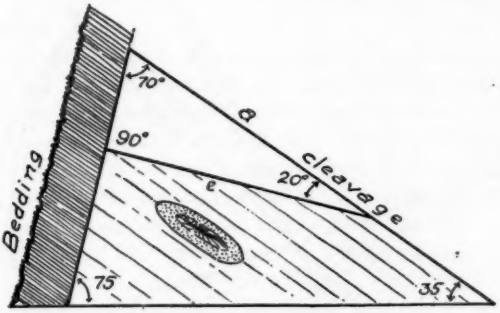


FIGURE 5.—*Relation of bedding to ovoid extension*
a: cleavage, e: normal on bedding.

In Figure 5, bedding dips 75° west, cleavage and extension 35° east. The angle between the two planes is 180− (75+35) = 70. If the component of elongation normal to the bedding is e, then:

$$\sin 70° = \frac{e}{a} \text{ or } e = a.\ \sin 70°$$

$$\sin 70° = 0.9397 \text{ and } e = 0.9397.a$$

This value can very readily be plotted, and the extension read quickly for any angle between cleavage and bedding after the extension in a has been determined.

REORIENTATION OF DATA

The calculation above furnishes quantities a, b, c, in the directions *a*, *b*, *c*. These quantities may be either shown as areas of equal extension (Pl. 9) or as directions.

The ellipsoid semi-axes a, b, c, or the diameters, 2a, 2b, 2c, are fixed orientations within a thin section and must be translated into the field. The angle between a, b, c, and the arrow on the slide determined the orientation of the ellipsoid in the slide. The thin-section orientation is marked on the sawed-off surface of the specimen and the angle between the arrow on that surface, and the strike of the surface determines the slide orientation. Finally, the orientation of the specimen is given by the attitude of the marked plane which has to be set up in such a way that it is identical with its original position in the field.

This orientation can readily be checked against cleavage readings, lineations, fold axes, and intersections as measured in the exposure.

For reorientation of specimen a lump of plastelline for mounting, a large-arm engineering protractor, several triangles, a chemical stand with clamp, and a small goniometer can be used.

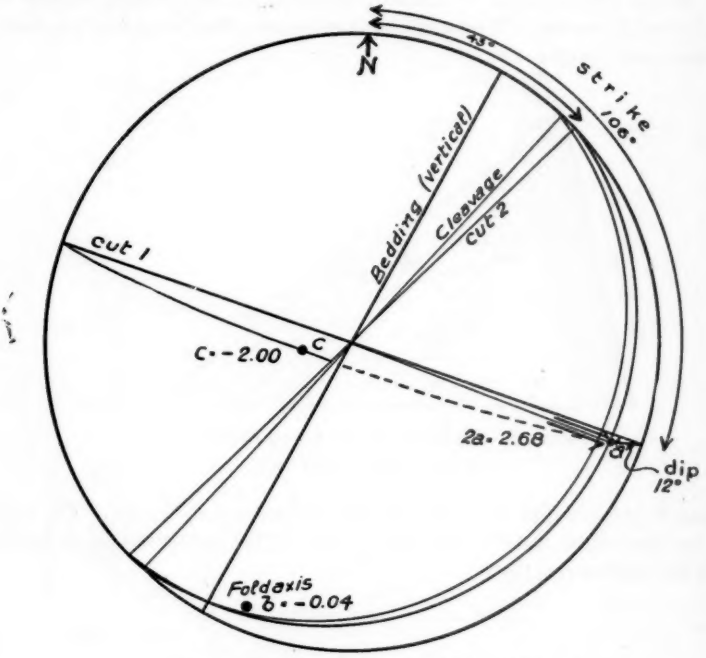


FIGURE 6.—*Plat of specimen 211 in equal-area net*
To determine angles and orientation of elements and axes.

After setting up the specimen the ground plate, plastelline, and specimen can be placed into a pan with water, and its surface will automatically show the strike of any surface on the specimen.

By far the easiest way of measuring the angles between planes, lines and planes, and lines is by plotting on a stereographic or equal-area net. Complicated geometric constructions are unnecessary, and the directions can be read directly, accurately, and quickly. The author has rarely seen this method used, and it is, therefore, outlined here.

Figure 6 is the plot of specimen 211, east of Mercersburg, Washington County, Maryland. An equal-area net was used, and the construction was made on a sheet of thin typewriter paper held in place by a thumb tack at the center. The two thin-section planes (saw cuts) are 1 and 2, striking 106° and 43°, dipping 86° and 12° respectively. The traces of these planes were drawn along the large circles. Cleavage is strong, strikes 40°, and dips 15° southeast. Bedding strikes 25° and is vertical. As can readily be seen in Figure 6, the fold axis dips 4° southwest and

strikes 25°. The intersection between the two thin sections is 82° as can be measured between the two poles along the large circle.

The arrows as marked on thin sections are shown as half arrows and are parallel in the two sections because in cutting the two straight sides, cleavage and the first cut were used in order to preserve the orientation.

Under the microscope the arrows were marked 360° equal to the zero position of the instrument. At zero the longest axes of the oöids in both slides are parallel to the half arrow on the slide, and thus the half arrow represents that direction without further computation.

On the cut specimen surface 1, the half arrow is 10° from the strike line and in the southeast quadrant. In cut 2 the angle is 64° in the northeast quadrant. These two angles as read along the two large circles indicating the traces of the two planes fall into point a. Inasmuch as slide 1 and 2 show the same value for the maximum, namely 11, this direction is the largest axis of the ellipsoid and its component 2a is +2.68 in the direction of the lineation as seen in the field and plotted in a in Figure 6. Its strike (horizontal projection) is 106° and its pitch 12° E-SE.

The mean axis, b, with the component b = −0.04 was measured only in slide 2. Here it is perpendicular to a and easily found as the direction of the fold axis.

c is perpendicular to the ab plane. Its value, −2.00, has been measured in cut 1 as perpendicular to a. Its position is shown correspondingly 12° W-NW of the center of the diagram.

The unusual relations of all elements can clearly be seen in Figure 6. a is in the cleavage plane at an angle of 97° to the fold axis. Errors and poorly oriented sections can also be detected at once. In this specimen the first cut deviates about 7° from the ac plane and the second cut 4° from cleavage. It is not always possible to cut both perfectly due to technical difficulties, shape of sample, and misunderstandings in the marking of the specimen for cutting. At the same time, this illustration shows the necessity of perfect orientation.

In the present investigation, all cuts have been plotted as described above.

SUMMARY OF METHOD

In summary, the different steps necessary are as follows:

(1) Location of suitable oölite beds if possible on the basis of geological maps.
(2) Structural inventory of the locality: Bedding, cleavage, fold axes, lineations, intersections of planar structures. Symbols should be plotted in a notebook with north as top of page.
(3) Determination of oölite deformation in three dimensions on weathered surfaces.
(4) Orientation of chosen specimens and tentative location of cuts to be sawed. Specimen shape should be considered because of sawing.
(5) Specimen is taken and labelled, *etc.*
(6) Permanent label should be painted and protected with shellac. Sample should be catalogued with its orientation plotted.
(7) Specimen should be well marked for sawing and shipped for grinding or oriented thin sections.

(8) Thin sections should be studied petrographically, structurally, and dimensions of oöids measured and listed.
(9) Averages, ratios, extension of a, b, and c, are calculated and best entered in a large list with numbers, localities, *etc.*
(10) Reorientation of slide in reference to saw cut and of specimens in reference to field orientation.
(11) Plotting of all values pertaining to a location on a stereographic net and thus determination of position of axes.
(12) Listing of all data in the main list for future use, construction of maps, charts, and tables.

In spite of the complicated procedure, the author can assure the reader that the individual stages become a definite routine after a short time, and if the material is handled every evening after a field day work can proceed quite rapidly. It is possible to do all this extra work along with mapping. Laboratory studies, however, consume more time.

The largest delay is usually in the grinding of thin sections.

DESCRIPTION OF OÖIDS

SPHERULITES

Oöids which show a black cross under the microscope with crossed nicols are most prevalent. They are never entirely free from concentric layers, and some are very finely laminated. In parallel light they all show varying degrees of radial structures as dust rows, streaks, cracks, and differences in the orientation of twinning and cleavage. Typical radial structure is seen in Figures 3, 4 and 5 of Plate 7 and Figures 1 and 10 of Plate 8. Figure 1 of Plate 8 illustrates the difference between a spherulitic oöid and a layered one (right). The radial arrangment is emphasized by cracks limiting large, wedge-shaped units. The black cross extends far beyond the original boundaries and into the matrix. An apron of newly-grown carbonate fringes the original oöid in parallel orientation. The right grain shows the dark cross only in a thick outer layer and the adjacent growth apron of new carbonate. The center is only an accumulation of carbonate crystals without parallel orientations.

Figure 2 of Plate 8 shows an elongated ellipsoidal oöid and radial growth outside of its primary boundaries. Under crossed nicols a black cross is partially visible. The original oöid was not spherulitic but growth takes place across the direction of maximum extension and after deformation.

The original spherulitic oöid is as a rule brown-yellowish, and secondary growth can be recognized as clear grains either outside or in spaces within the oöid or between its layers. Recognition of the original oöid is of some importance because the determination of the deformation ratio depends on the original volume and shape. Additional growth increases the volume; solution along boundaries decreases it.

In slides of slightly above standard thickness, the yellow original grain can easily be detected.

Individual radii of the spherulites are not fibrous but consist of rows of small

crystals in parallel orientation. Fibrous aggregates have not been found. It may well be that aragonite fibrolites have changed into calcite but that the orientation has been retained.

Internal structures are rather similar. Cracks, dust rows, or inclusions radiate from a center, interrupted by concentric ringlike layers or membranes of varying thickness. There may be many rings as in Figure 2 of Plate 2 or only two or three. Centers are the rule but not all sections show them. Many cuts pass above or below the center as well illustrated by Brown (1914, p. 763, Fig. 1). The position of the cuts also influences the apparent size of the oöid in a thin section. Oölites that show no cores have been cut off-center and therefore show an apparent size less than the true one. In measuring it is therefore preferable to use spherulite sections with centers or cores.

Spherulitic growths on fragments, uneven sand grains, lumps, or objects of almost any shape are common. If the fragments are elongated as in Figure 2 of Plate 7, growth is on the boundary of the object and not spherical. Layering may also parallel the original shape; thus long cylindrical and irregularly elongated bodies may result. These oöids are excluded in the deformation analysis but may indicate the direction of bedding and thus prove very useful (Pl. 7, fig. 2). Small elongate fossil fragments, minerals, mineral clusters, or mud lumps are mostly included in spherulite centers if the newly growing fibre can overcome this eccentricity through healthy growth as in Figures 7 and 8 of Plate 7 where spherulitic growth alternates with layers.

SHAPES OF SPHERULITES

Normal undeformed spherulites (Pl. 7, figs. 3, 4), are very nearly spherical with spherical layers of dark material and radial growth from a center. Deviation from the spherical shape is well below 10 per cent of the diameter and remains unoriented; in other words the slightly longer diameter is never in one direction, but its orientation "boxes the compass."

Primary shapes can be recognized easily by color, orientation of spherulite radii or spherulitic growth, or by orientation. Many spherulites with elongated centers and parallel to bedding can be eliminated. Figure 2 of Plate 7 shows such fragments in relation to bedding. It is also advisable to discard oöids with very distinctly elongated centers. Not all eccentric or odd-shaped centers are disturbing, however, if the outer layers have covered the irregularities (Pl. 7, figs. 7, 8).

Deformation can be recognized particularly if two mutually perpendicular sections are available. Flat shell fragments or elongate bodies parallel to bedding show essentially similar dimensions in the two sections. Uniformly elongate and spindle-shaped oöids show similar proportions in one section and widely different ones in others. Deformed oöids are similar; primary differences are usually distinctly dissimilar. In Figure 5 of Plate 7 many dissimilar centers can be seen in oöids of similar size and shape. Primary differences are in composition, shape, and size. Deformation, however, is always in one general direction.

Addition and subtraction due to growth or solution is also readily recognized.

Growth occurs mostly as light rims of crystalline carbonate and always in the direction of the original spherulite radii. If deformation is strong and the spherulite strongly extended, growth is much more intense parallel to elongation, and there may be none perpendicular to it.

Figure 3 of Plate 8 shows two sections of one specimen. Growth is strong and easily recognized in the less deformed oöid. The other one is surrounded by small calcite grains, and there is no increase due to growth. In Figure 1 of Plate 8 the spherulite to the left has grown to almost twice its width by secondary addition. Almost all spherulites have grown to some extent.

Solution can be seen in Figure 6 of Plate 8 and in Figure 3 of Plate 4. Well-layered oöids with spherulitic layers (light) are injured along ragged surfaces (dark irregular lines) which cut into the layers and leave the oöids narrower than originally. Some cores are entirely stripped of their cover and touch their adjacent neighbors. Obviously a good deal of material is missing.

Growth and some solution can be seen in Figure 10 of Plate 8. Fine, fibrous light carbonate grows in the direction of maximum extension, and solution has damaged the central oöid along the right contact.

LAYERED OÖIDS AND PELLETS

Layered oöids and mud pellets are also present in almost all slides. The layered oöids may consist of a crystalline core with layers of varying coarseness, chemical composition, color, or structure. Very fine shale is most common and usually much darker due to iron oxide or organic material. Typical layered oöids are seen in Figures 4, 7, 8, and 12 of Plate 7 and Figures 1 and 6 of Plate 8. Some layers may be faintly spherulitic. Figure 4 of Plate 8 demonstrates the variability of these oöids very well. In the left oöid a crystalline light ring is between a fine-grained center of shale and a somewhat coarser outer shell showing faint parallel orientation in the direction of maximum elongation. The central oöid has a crystalline core and a dark outer shell. The quartz grain is well-rounded, and its zonal growth beyond the original limits can be seen in inclusion rows. All oöids in the figure are elongated by similar amounts and in the same direction.

Spherulites and nonspherulitic pellets in about equal proportions are shown in Figure 6 of Plate 7. Secondary growth is radial and on all oöids. Deformation is about 35 per cent and has affected all oöids uniformly. Size and shape of the pellets varies more than in the spherulites. In spite of a distinct irregularity, the elongation is uniform and readily detected.

Some pellets (Pl. 7, figs. 12, 15) are very irregular, layered, but uniformly deformed. Measurements have not been made because of the irregular initial shape of the lumps. They can scarcely be assumed to have been spherical before distortion.

Very regular and usable shaly oöids are shown in Figure 5 of Plate 8. They are well-rounded, uniformly elongated in a matrix of clear, rather coarse carbonate (probably all calcite). The centers are small clusters of carbonate crystals with some replacement, and secondary crystallization can be seen in the center of the picture. A fracture has been filled with very clear and untwinned calcite.

FIGURE 1. UNDEFORMED CARBONATE GRAINS IN HIGHLY DEFORMED MATRIX
With distorted oöids and mud pellets. Loc. 310, ¼ mile south of Stoughstown on U. S. 11, Newville quadrangle.

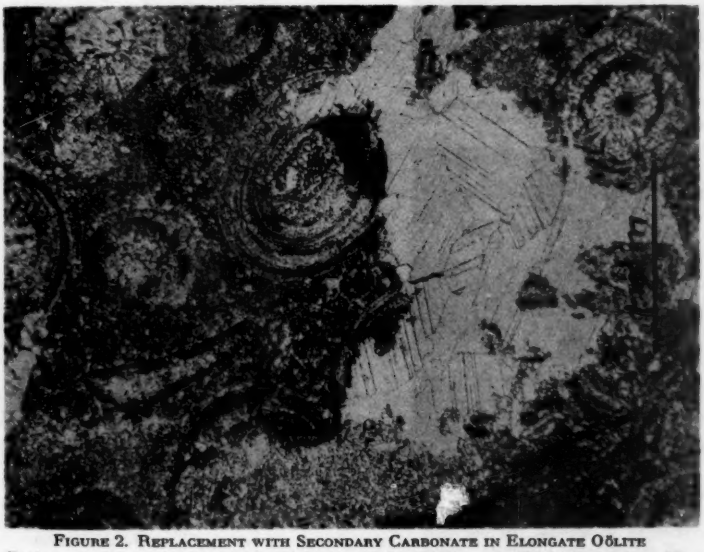


FIGURE 2. REPLACEMENT WITH SECONDARY CARBONATE IN ELONGATE OÖLITE
Replacement is readily recognized and does not follow primary or older textures. Loc. 201, northeast of Reid, Chambersburg folio, northern boundary of Washington County map.

PEBBLES VERSUS REPLACEMENT

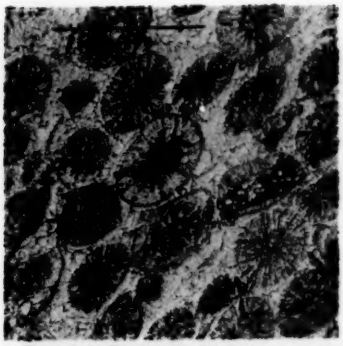


FIGURE 1. DEFORMED SPHERULITES IN POSTDEFORMATIONAL MATRIX
Loc. 397.

FIGURE 2. SPHERULITE WITH RADIAL FRACTURES
Probably due to compression. Growth aprons grow into matrix. Deformation 40 per cent. Loc. 344 A.

FIGURE 3. OÖLITE WITH STRONGLY DEFORMED OÖIDS
Partly with chert centers and solution in cleavage planes. Loc. 404.

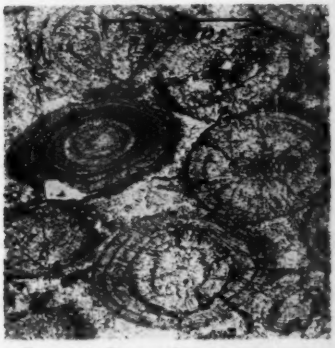


FIGURE 4. RINGED SPHERULITES WITH APRONS
Cleavage becomes visible from left to right. Deformation 30 per cent. Loc. 266.

FIGURE 5. COMBINATION OF SPHERULITES WITH MUD RINGS
Deformation in *ac* exceeds 100 per cent. That oöids are flattened spindels is shown in *bc* section. Loc. 204.

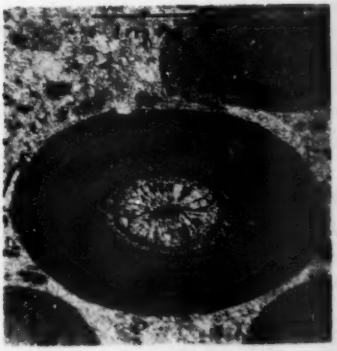


FIGURE 6. CONCENTRIC MUD-PELLET OÖLITE WITH SPHERULITE CENTER AND EVEN DEFORMATION
Parallel texture is faintly visible within oöid in the muddy portions. Loc. 287¼.

Entirely massive, unlayered pellets are mostly irregular and can only rarely be used. Examples can be seen in Figs. 1, 9, and 13 of Plate 7 where they occur together with oöids. Layered pellets and those with centers can be used if their ratios are fairly constant.

Shale pellets seem to be merely parts of an unconsolidated sediment, torn loose and sometimes sufficiently rolled to be rounded and possibly layered. Some large lumps contain oöids as in Figure 9 of Plate 7 and are considered to be pebbles. Quartz grains are frequently more abundant in these pebbles and migrate into the matrix as the lump gradually disintegrates (Pl. 7, fig. 11).

Such pellets have been described in the literature and seem common. Hatch and Rastall (1938, p. 170) observe that "in North America, pellet limestones are particularly well seen in parts of the Stonehenge and other Ordovician limestones of the Appalachian Mountains." They are thought to be due to animal action.

"PSEUDOÖLITH"

The present investigation uses oölites as means of measuring deformation, and other design in a rock like crinoid stems, or other fossils may serve as well. Determination of the amount of distortion, however, is closely linked with changes which are not due to mechanical distortion like growth and solution, styolites, dolomitization, and others. The origin of oölites enters the measurements as far as the recognition of processes is important in the determination of primary dimensions. Many papers on oölites contain definitions and can roughly be divided in two groups: one which restricts the term oöid to "spherical formations which are characterized by concentrically layered or radial structure and can thus be recognized as mineral precipitations from solutions" (Bornemann, 1886); and a second group which includes rolled spherical fragments, round pellets, and similar shapes. Bornemann describes the second group as follows:

> "In thin section (pl. IX, Fig. 5) one recognizes easily that the presumed oölite structure is based only on the spherical shape of the grains, which make up the rock. These are not forms which are precipitated from solution as radial fibrous or concentric bodies but [they] are fragments of crystalline limestone rolled and worn in moving water. They have been mixed with darker grains of marl and fossil fragments of about equal size as fine limestone sand and have been cemented later by penetrating lime into a firm rock."

Bornemann called these fragments "pseudoölith."

He furthermore refers to a paper by Frantzen (1881) who describes "oölite grains without radial structure, but composed of several crystals with different positions of their axes. These oölite grains resemble rock fragments, rounded through wave action."

Bornemann's pictures could have been taken from some of the present author's slides, and his and Frantzen's description applies to what was tentatively named pebbles before finding the above-cited descriptions.

Gaub (1910) opposes Bornemann's interpretation but describes nonradial, crystalline, spherical bodies without centers and mostly of rhombohedral dolomite. He interprets the same kind of material as secondary replacement and recrystallization.

"Pseudoölites" are present in 28 specimens some of which are composed of crystalline pebbles only (Pl. 7, fig. 10; Pl. 8, fig. 7).

Dolomite clusters with generally spherical outline are shown in Figure 1 of Plate 7, and Figure 9 of Plate 8. Some single grains are in a rather fine-grained dark muddy matrix.

Undeformed "pseudoölites" occur together with highly deformed genuine oöids in Figure 1 of Plate 3, Figure 1 of Plate 7, and Figure 9 of Plate 8. The co-existence of undeformed pebbles and deformed oöids becomes a tool in the determination of the history of the rock.

Krech (1909) must have observed similar "oölites" and called them "micropebbles".

These "micropebbles" are useless for the deformation analysis because they remained undeformed. They are confusing in hand specimens because they are easily mistaken for oöids, but they are important because they emphasize the existence of two stages: a more resistant and crystalline one in an environment of soft and possibly muddy material which flowed. The writer believes that these pebbles are fragments of a crystalline carbonate rock which have been rounded, either by wave action, or by abrasion by fine mud which drifted over them and rolled the fragments. They seem to belong to the early history of the rock and to the phase of the accumulation of the material.

They are not related to growth from a center or around it because they have no centers (Pl. 7, figs. 1, 10; Pl. 8, figs. 7, 9) growth structure, or zonal layering. They are composed of several grains, and it is significant that the grains have sharp edges and corners in the center but are smooth and rounded at the periphery (especially Pl. 8, fig. 9).

Typical pebbles consisting of many grains are shown on Figure 3 of Plate 2, and pebbles with only one or very few grains can be seen in Figure 1 of Plate 3 where the soft oöids are highly deformed. The same slide is also shown in Figure 1 of Plate 7, and it can here be seen how the matrix flows around the pebbles.

DETRITAL GRAINS

Detrital material is common in the Paleozoic oölites as seen in the many round sand grains (Pl. 7, fig. 11), pellets (Pl. 2, fig. 1), and fragments of more or less consolidated oölites (Pl. 7, fig. 11). In Figure 8 of Plate 8 a large rounded fragment of oölite is composed of six large spherulitic zonal oöids and is surrounded by clear calcite. This pebble occurs together with a cluster of carbonate crystals, single well-rounded grains, and normal spherulites. All the spherulites in this specimen may have come from older oölite similar to the pebble in Figure 8 of Plate 8 but more broken up. The pellets and other units may have come from the same source oölite or may have been added at the new location.

Reworking and redeposition is shown in Figure 11 of Plate 7 and Figure 4 of Plate 5. A fairly large oölite pebble contains portions of 3 spherulites which are held together by shaly quartz-free matrix. The spherulites are all partially eroded and rounded without injury to their shapes. In the new environment there are added

oölite fragments which have been partly healed, pellets, unassorted elongate fragments of shells which show spherulitic growth, and many well-rounded quartz grains. The parallel orientation in Figure 11 of Plate 7, is due to parallelism of elongate units including the long pebble and the quartz grains. This arrangement seems to parallel bedding.

Single well-rounded grains of quartz and calcite are common in almost all slides. Figure 11 of Plate 7, shows many quartz grains. In Figure 7 of Plate 7, sand grains have formed centers in layered and zonal oöids. A section of well-rounded sand grains is shown in Figure 11 of Plate 8 (lower column). Almost all detrital grains show a tendency to grow into better complete crystals after they have become embedded. In Figure 12 of Plate 8, four quartz sand grains show secondary growth and the future outline of crystals.

Calcite sand grains are shown in Figure 11 of Plate 8 (upper column). They are of the same order of magnitude as the quartz grains, as well or better rounded, and also thought to be detrital. These grains are much larger than the average grain size of the limestone and approximately the size of oöids. Figure 8b of Plate 8, shows one large round grain surrounded by mud pellets and twinned calcite and slightly larger than the oöids below. A rounded and twinned calcite grain has grown into a much larger crystal in Figure 15 of Plate 8, and another calcite grain occurs next to an oöid in the same figure at the left.

Detrital carbonate grains are abundant in all slides. They can readily be distinguished because they are well rounded, of the same order of magnitude as the oöids, and show the same yellowish-brown tint as the primary part of the oöids. All of them are intensely twinned.

SECONDARY GROWTH

All mineral growth in addition to the original size or outline of oöids and all replacement features are included in secondary growth. The present textures of all samples are determined by it, and the matrix consists of it. The term is not meant to imply any definite position in the chronological sequence of events.

Very typical for secondary mineralization and replacement are the euhedral quartz grains as shown in Figure 12 of Plate 8. The outline of new quartz crystals is clearly visible even if growth has been interrupted before the crystal was completed. Figure 13 of Plate 8 shows a rounded quartz grain and an elongate crystal under crossed nicols. It is rather remarkable that the quartz replaced spherulites more readily than matrix.

Growth aprons around oöids are the most prevalent form of secondary growth, and there are no slides without it. As a rule new, clear carbonate outlines pellets, spherulites, and single grains. Spherulites have always grown beyond their original limits maintaining the orientation. Radial growth aprons are large and may fill the interstices completely (Pl. 7, figs. 6, 9; Pl. 8, fig. 9). Pellets are not always surrounded by aprons and only rarely by very large ones. Secondary carbonates seem to grow better on carbonate spherulites. Aprons in Figure 8 of Plate 7 are small possibly because the outermost layer of the oöids is shaly. Very small rims in a muddy

matrix may well be related to the lack of carbonate present in a mudstone. The lack of aprons in Figures 4 and 5 of Plate 8, can scarecely be attributed to the absence of carbonate because the matrix consists of well-crystallized and clear calcite. "Micropebbles" also remain rather free of growth aprons as can be seen in Figures 7, 8, 9, and 15 of Plate 8.

Single carbonate grains tend to grow into larger units just like quartz. As a rule the original round grain is yellowish and slightly darker than the new fringe. A thin rim of inclusions may outline the original grain as in Figure 15 of Plate 8. Cleavage or twinning lamellae transsect both the old core and the new fringe; under crossed nicols their parallel orientation becomes still more apparent. Figure 15 of Plate 8, shows a detrital grain without secondary growth and an adjacent spherulite. They are of equal size and both are nearly spherical.

Replacements are comparatively rare. Quartz replaces carbonates in the growth of quartz as outlined above. Chert replacement is extensive only in two specimens but has been observed in many slides on a small scale. Figures 8c and d of Plate 8, show chert replacing carbonate. Most of the silica however is detrital and concentrated in quartz-rich pellets.

Calcite replacement is well shown in Figure 2 of Plate 3.

BEDDING

Bedding is recognized in most of the larger exposures, particularly if deformation is moderate and cleavage lacking or only weak. With increasing distortion, however, stratification is obliterated, and cleavage becomes the only visible structure. If recrystallization or mineralization accompanies deformation, cleavage may readily be confused with bedding, and it becomes necessary to search for distinct lithologic differences. Where specimens are oriented in the field, the deformation directions can readily be related to the bedding, cleavage, lineations, and axes of folding.

In thin sections, bedding can also be recognized either in the orientation of primarily elongate forms like shells, fragments, and lenticular pebbles, or the planes themselves may have been cut by the section. Many specimens show good bedding in all degrees of deformation.

Stratification becomes visible as changes in lithology, fine shaly partings separating limestone beds, or as cölite beds in contact with nonoölithic mudstone, marble, or ordinary limestone. Bedding planes are always loci of solution phenomena like stylolites, or of deposition and replacement of silica or carbonate.

Figure 8 of Plate 7, shows very distinct bedding as thin shaly layers in otherwise clear limestone. The cöids are elongated at a large angle to the strata. In Figure 6 of Plate 7 a thin dark layer separates two layers of oölite of slightly differing color and grain size. Elongation is also almost at 90° to the plane. Intense crenulation is visible in Figures 12 and 13 of Plate 7 where the distortions of oöids are 40 and 30 per cent. Bedding is here visible as dark layers studded with quartz grains which have been left when carbonates were carried away. Shaly and carbonaceous materials are also remnants of pellets. As the lateral distance decreased the bedding plane was crenulated.

Solution along bedding planes is visible in Figure 5 of Plate 5, and Figure 7 of Plate 7, where oöids are cut and eaten into.

Extreme deformation of oöids and bedding is shown in Figure 14 of Plate 7. Lateral reduction forced the bedding plane into sharp folds, emphasized by flowage in the direction of maximum extension.

The close relation between oöid deformation and the degree of crenulation of bedding planes is a clue to quantitative analyses where cöids are absent. Systematic measurements of wrinkles in thin sections and counts of folds may provide rather valuable data on the distortion of a complex.

MATRIX

The matrix is probably the largest factor in the deformation of cöids and also the most difficult to evaluate. There are two principal types of material: crystalline carbonate and shale in varying proportions. Some oölites are dark and cryptocrystalline with only some light oöids of crystalline carbonate (Pl. 7, fig. 6); others consist of pellets in a clear and light crystalline matrix (Pl. 8, fig. 4). Between the two extremes are many gradations.

It has not been possible to determine the degree of deformation which is recorded in the matrix. Several possibilities have to be considered:

(1) The matrix may be much softer than the oöids. The latter would then be protected against deformation by the soft matrix and remain undistorted. This seems indicated in the relation between hard "pseudopebbles" and matrix.

(2) The matrix is crystalline, and the oöids are soft. This should be recognizable as mylonitization or granulation of matrix.

(3) Both cöids and matrix are crystalline and equally hard.

(4) Matrix and oöids are soft, pliable, and deformed at the same rate.

All other possibilities are probably represented, but they cannot always be clearly recognized because they grade into each other.

There seems to be little difference in the deformation intensity of matrix and cöids as shown in ratios of oöids and pellets within one slide. Figure 6 of Plate 7 for instance shows mud pellets and spherulites side by side with equal deformation ratio, but different sizes. In Figures 12 and 13 of Plate 7 oöids and pellets possess an equal ratio.

SEQUENCE OF EVENTS

A summary of the history of cölite deformation and deformation is presented in Figure 7.

The source material of the oölites can in part be recognized in detrital material. Carbonates in solution must also have been available.

Many detrital constituents served as loci for growth of oöids but a large number remained uncovered. This may indicate the degree of concentration of the solution. If saturation were approached all forms may have been covered by spherulitic growths.

The Geologic Setting of the Oöid
Crystalline aggregates
Fossil fragments
Oöids in pebbles or loose
or they grow en route
Carbonates in solution
or in place of deposition
Feeding relicts into cores of oöids, micropebbles, sand
SEDIMENT: Mud - Sand - pebbles
MIXTURE OR SEPARATION
SEDIMENTATION
and rolling on beach
Some of them remain undeformed
CONSOLIDATION
DEFORMATION after oöids have arrived
On the scene but before crystals grow on them
They were all deformed at one time
GROWTH of new crystals in new environment and space begins during deformation and continues beyond
MATRIX
REPLACEMENT
APRONS
Fractures and Joints
The end phase of deformation: Pulsating, cleavage, fissures in Calcite
Healing and Annealing
Oolitic Limestone

FIGURE 7.—*Schematic diagram of the sequence of events*

The mixture of detrital components, mud, carbonate ooze, and cöids was then deposited in beds and covered by other layers of varying thickness and composition. This phase is here called sedimentation.

The cölites were deformed after sedimentation but before consolidation and a regional pattern was superimposed on the sediment. This is shown by distortion of soft components but not of the detrital crystalline aggregates.

Growth of carbonate aprons and extension of spherulites into the matrix occurred in a postkinematic stage because carbonates grew on deformed cöids but itself remained undeformed.

Overlapping of these stages is indicated however by cleavage and twinning of calcite and herringbone pattern in some of the intensely distorted cöids.

Crystallization of matrix was followed by fracturing and healing of fractures by clear carbonate.

DESCRIPTION OF DEFORMATION

The present appearance of the deformed cölite depends on its original composition, on the intensity of the distortion, and on postdeformational crystallization.

Crushed cölites have been found only in one slide.

Tectonic deformation ranges from 0 to several hundred per cent and is illustrated in the photographs and camera lucida drawings which are also intended to show the variability of the deformed cöids. Hardly two of over 400 thin sections are alike, and it is difficult to compare types. Orientation of deformation, however, is constant and easily recognized in large areas, in spite of the variability of the cöids. Bedding has become obsolete, and new alignments transsect it.

Two kinds of elements can be distinguished: (1) hard and resistant units composed of "pseudopebbles", and detrital sand grains and (2) deformed, pliable mud pellets, spherulites, and matrix. The former are undeformed or surrounded by pliable material but may also break up into angular fragments. Examples of this type have been described above and are shown in the following illustrations: Figure 3 of Plate 2; Figure 1 of Plate 3; Figures 1 and 10 of Plate 7; Figures 7, 8, 9, and 15 of Plate 8. Fragmentation of pebbles is indicated in Figure 7 of Plate 8.

All the elements of the second group are deformed by the same amount within one slide and there is little indication of differences of ratio between mud pellets or spherulites. Harder cores may, however, lag behind and show less distortion than the outer layers of an cöid. Irregularities can be overcome by measurement of many cöids and elimination of freaks. Only the best material should be used.

Undeformed cöids are recognized by absence of orientation of eccentricity and a wide range (Fig. 3). The matrix lacks flowage structures and orientation of components (Pls. 1, 2; Pl. 7, fig. 3, 4).

A deformation of 10 per cent can already be recognized easily in an alignment of the longest axes of cöids, but matrix and mud pellets remain unaffected (Pl. 7, fig. 9).

Twenty per cent deformation is very obvious and comprises spherulites, pellets, and matrix (Pl. 4, fig. 1; Pl. 8, figs. 1 and 5). If a bedding plane has been included in the thin section it is mildly undulating and due to lateral reduction of the maximum deformation axis at a large angle to the bedding plane as in Figure 6 of Plate 7.

Thirty per cent deformation includes all components, and cleavage begins to appear as in Figure 4 of Plate 4 or Figure 8 of Plate 7. Bedding planes may suffer considerable crenulation (Pl. 7, fig. 13), and solution plays an important part in the accumulation of residue in bedding planes. Cross fractures are filled with white carbonate in Figure 5 of Plate 7.

As intensity of deformation increases, distortion differs slightly in layered oöids and spherulites in that the former remains smooth and seems to conform more readily. The distortion of spherulites is accompanied by radial fractures. The layered oöid in Figure 6 of Plate 4 is deformed 50 per cent without difficulty, the ends are still smooth but a faint parallelism of particles in the cleavage direction appears (*see* also Pl. 4, fig. 5). The spherulite in Figure 2 of Plate 4 is deformed only 40 per cent but has begun to fracture radially. The same stage has been reached in Figure 9 of Plate 8 where the primary oöid is elongated and a secondary apron has grown beyond its limits. To the left of the distorted oöid is an undistorted "pebble".

The contrast between mud pellets and spherulites is visible in Figure 2 of Plate 6. Sperulites are here fractured and elliptical, but the mud layer has exceeded that deformation. The layer is thicker at the ends and has begun to fray.

Fraying becomes more obvious with increasing distortion (Pl. 6, fig. 1; Pl. 4, fig. 3). Measurements become more difficult at that state because it is probable that some of the material has been lost. In well-layered oöids the difficulty may be overcome by measuring an inner layer, but accuracy decreases with increasing deformation. This is partly compensated by increasing regularity of orientation.

Deformation beyond 100 per cent is rarely measurable in the ac plane, but a minimum value may be measured in the combination of the bc and ac planes. Figure 5 of Plate 4 pictures deformation exceeding 100 per cent in the ac plane but a well measurable distortion in bc. The cöids have become long and flattened spindles. A similar situation is shown in Figure 3 of Plate 8 where ac and bc cuts have been drawn for comparison.

Maximum deformation shown is in Figure 14 of Plate 7. The cöids are still recognizable, bedding intensely crenulated, a cleavage dominates, and measurements are barely possible and represent minima only, due to fraying in the direction of the longest axis.

Secondary replacement is localized and easily recognizable (Pl. 3, fig. 2; Pl. 8, fig. 12) Carbonate has filled available spaces and is generally restricted to the matrix, with little influence on the cöids. Much of this growth is in aprons around cöids and especially in the enlargement of spherulites. Postcrystalline deformation is visible in the matrix and spherulites in twinning of carbonate grains and herringbone pattern at the ends (Pl. 5, fig. 1). Since deformation of the cöids is many times that of the matrix the author thinks that the latter crystallized rather late and suffered deformation only during the late stage of deformation.

VARIATIONS OF DEFORMATION INTENSITIES

GENERAL REMARKS

Deformation intensity varies (1) with physical properties and thus with composition of oöids and matrix, (2) regionally with respect to location in the South Moun-

FIGURE 1. CONCENTRIC LAYERS ON SPHERULITES
Elongated 20 per cent. Carbonate aprons grow on deformed oöids in the direction of the spherulite until they meet neighboring aprons. Boundary outlines in ink. Bedding separates dark from light bed. Loc. 380.

FIGURE 2. CONCENTRIC OÖIDS ELONGATED 50 PER CENT
Bedding across extension. Loc. 247 b.

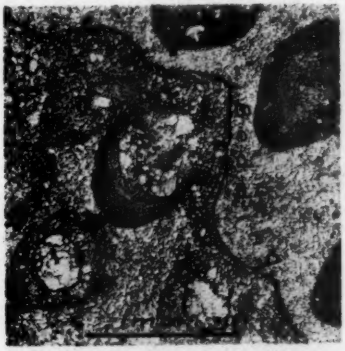


FIGURE 3. MUD PELLETS WITH CRYSTALLINE CORES DEFORMED AT LARGE ANGLE TO BEDDING
Considerable solution after deformation.

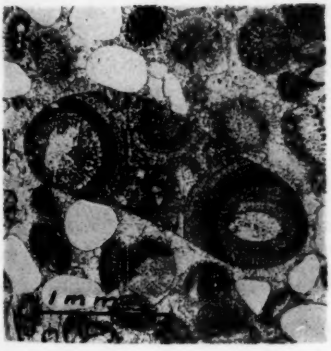


FIGURE 4. LARGE PEBBLE OF OÖLITE IN SANDY OÖLITE
Quartz grains white. Many fragments are healed to form spherical oöids. Bushberg formation, Missouri. Specimen by H. R. Gault.

FIGURE 5. DEFORMED MUD PELLETS
Seventy per cent deformation. Three micropebbles of round carbonate grains undeformed. Bedding: black zigzag studded with carbonate. Matrix: finely crystalline carbonate. Loc. 2 miles N. of Chewsville.

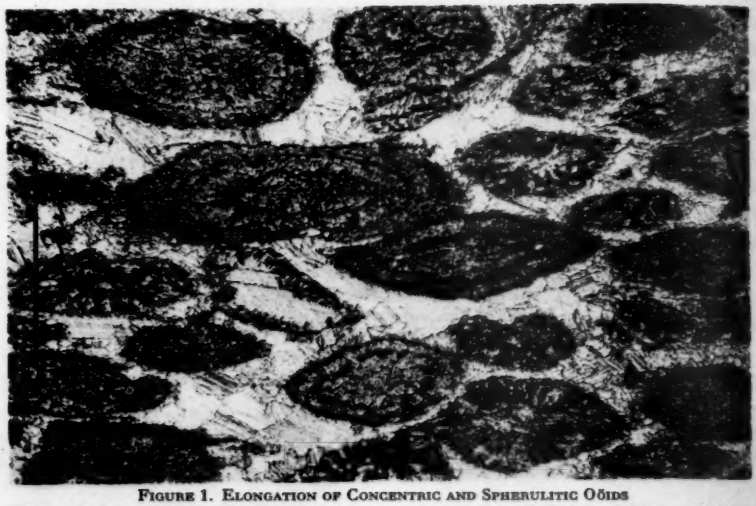


FIGURE 1. ELONGATION OF CONCENTRIC AND SPHERULITIC OÖIDS
Has reached 60 per cent, and the ends begin to fray. Matrix clear, little-deformed twinned calcite shows some strain. Loc. 313 N. of road intersection 2 miles west of Scotland, Chambersburg quadrangle.

FIGURE 2. SPHERULITES WITH MUD RINGS WHICH PREVENT GROWTH OF APRONS
Deformation results in thickening of mud rings in the direction of elongation. Deformation 40 per cent. Loc. 328, Carlisle-Dillsburg road, north slope of Stony Ridge, Carlisle quadrangle.

DEFORMED AND FRAYED OÖIDS

tain fold, (3) in relation to other structure elements, like lineation and cleavage, and with position in a fold.

PHYSICAL PROPERTIES

Undeformed detrital grains and "micro pebbles" have been dealt with above. Chert nodules also remain undeformed if chertification takes place prior to deformation. Later introduction of silica merely preserved existing shapes as chert, replacements, or quartz crystals as in Figures 11–13 of Plate 8. However, the author has found no elongated oöids replaced by chert which seems to indicate chertification prior to deformation.

REGIONAL VARIATION (PLATE 9)

Maximum deformation intensities have been plotted on a map of the area for each observation point that yielded reliable values. The maximum value is mostly a (*a*), but in some instances b (*b*); a equals b at some localities, and then the a = b value has been used.

Lines of equal intensity are shown for 20, 30, 50 and 100 per cent deformation. Plate 9 shows that the intensity of deformation increases gradually toward the core of the South Mountain fold. This can be seen best in those sections where the uplift rises rather abruptly and with few subordinate folds in front of it.

An excellent section was measured along the Williamsport-Boonsboro highway and to the north and south of it. The values are 10, 33, 43, 73, 80, and 100 per cent. The westernmost value is 20 per cent and occurs in the lower limb of an asymmetrical fold; the next value to the east—10 per cent— is in the upper limb. In the Funkstown section to the north the values increase from 20 through 30 and 80 to 100 per cent. At New Scotland in the Chambersburg quadrangle, 18 and 20 per cent rise to 35, 45, 52 per cent and beyond.

Near Sharpsburg a low value of 12 per cent is within a higher area of 20 to 50 per cent. The sample is an oölite megascopically, but the oöids are all pebbles and well-rounded carbonate sand grains, and undeformed in a matrix of shale.

North of Hagerstown high values appear abruptly in the extension of a plunging fold. In the upper limb of the same fold further north low values appear. This general confusion is not surprising in a series of asymmetrical folds in which the lower limbs suffer more intense deformation and are in part overridden by the rest of the folds.

Some samples may have been taken from the vicinity of faults, and this contributed to the more intense deformation.

Cross faults may be responsible for indentations in the lines east of Funkstown where the northern part seems to be offset toward the west.

If a larger number of values were available more details could undoubtedly be worked out. It would be possible to trace intensity lines more accurately, to detect cross faults, thrusts, and gain additional information.

VARIATION AND STRUCTURES

The differences due to position of a sample within a fold are well illustrated in the triangular area between Greencastle, Waynesboro, and Scotland. Axes in this

region plunge southwestward and are offset in en echelon pattern. This is well shown on the Chambersburg quadrangle map (Stose, 1909). Between Scotland and Waynesboro at least three folds plunge to the southwest, one near Stonehenge, a second one at Elbrook, and a third at Waynesboro. In Plate 9 the Waynesboro

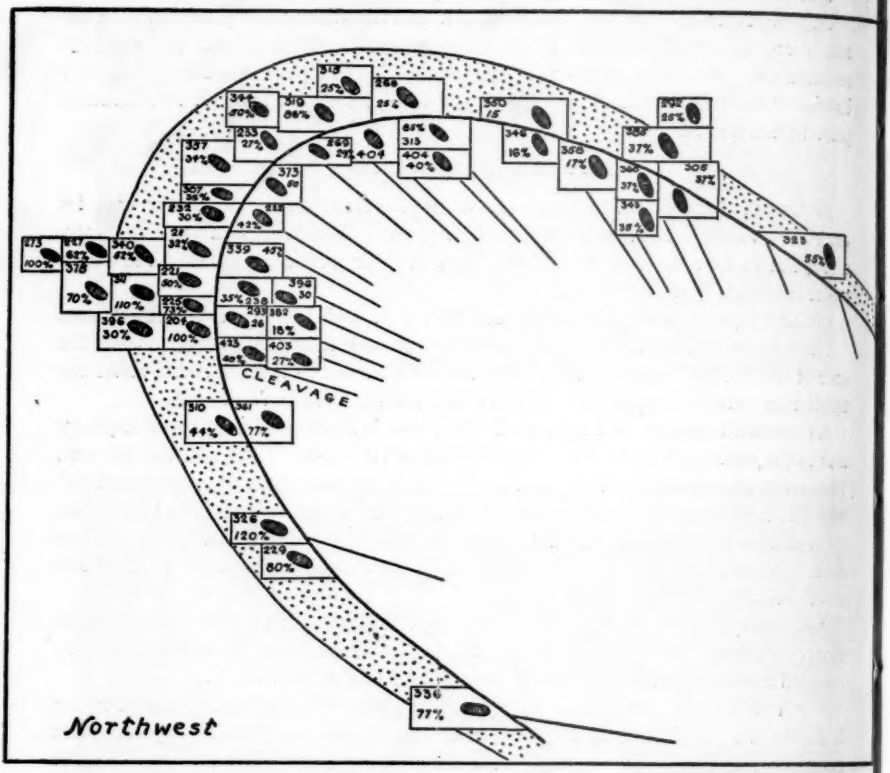


FIGURE 8.—*Reconstruction of fold*

Plat of *ac* sections. Pl. 12, figs. 1–5. Cleavage is arranged in a fan opening to the northwest. Most observations are in the steep limb of the asymmetric fold.

formation as copied from Stose's map reflects these folds. Oölite samples were consequently taken from various parts of those folds and not always from the lower limbs. Low and high values alternate therefore in a rather broad area and lines of equal intensity become confused and indented.

Positions of cöids are illustrated in Figures 1–5 of Plate 12 for the more important points. Intensities are in parentheses in per cent. The specimen are platted as cross sections (*ac*) normal to the fold axes, showing the maximum and minimum oöid axes, cleavage, and bedding in their position in space.

The same values have then been used in the construction of Figures 8 and 9. The

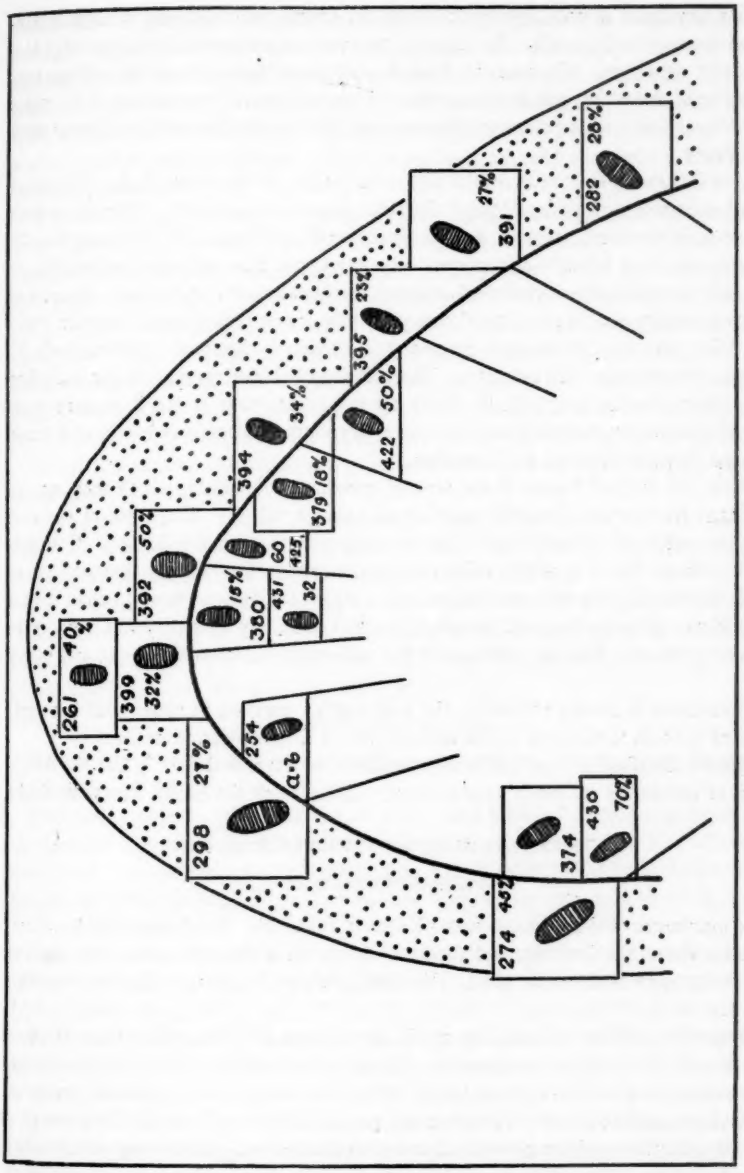


FIGURE 9.—*Reconstruction of upright fold*

Plat of 22 sections Pl. 12, figs. 1-5 into an upright fold. Of the large number of observations only few are in an upright fold.

bedding has been pieced together to form an overturned fold and a slightly fan-shaped cleavage in Figure 8. In Figure 9 the same process produced an upright fold with steep cleavage. The western limb is somewhat steeper than the eastern one.

In spite of the rather schematical plats in Figures 8 and 9 the position of the oöids in relation to folds, the relation to cleavage, and the distribution of intensities appears very clearly.

Figure 8 shows a concentration of higher intensities in the lower limb. The average value between specimen 336 and the axial plane is 56 per cent. The upper limb average is 36 per cent. There are 4 values exceeding 100 per cent, 9 values over 70 per cent, and only 3 below 30 per cent. In the upper limb no value exceeds 90 per cent; only 2 exceed 65 per cent and there are 8 values below 30 per cent. In spite of the irregularities the upper limb shows generally lower percentages than the lower one. The average deformation intensity is obviously less: no value exceeds 70 per cent, the average is 36 per cent. The fact that this deformation is generally less is also shown in the map (Pl. 9) where all the points near South Mountain show greater deformation intensity and structural asymmetry, largely visible in an intense eastward-dipping cleavage and lineation.

Within the fold of Figure 8 are several groupings of values, which may not be significant in view of the small number of platted values. The crest of the fold shows low values to the east (right) and then higher ones, all in the thirties. Counterclockwise from the axial plane, values are bunched together because that position of beds is the most frequently met in the field. From the distribution of values within this fold one may be tempted to conclude that intensity of deformation varies in different parts of a fold, in addition to the difference between the lower and upper limb.

Deformation is closely related to the fold and its position in space, and the symmetry of the fold is reflected in the distribution of deformation intensities.

Regional distribution has not been considered in Figures 8 and 9, but the distribution of intensities is closely related to the influence of the South Mountain fold.

ORIENTATION OF DEFORMATION AXES

REGIONAL ORIENTATION

The maximum oöid axes have been plotted in Plate 10. Black spots are localities, the arrow shows the direction and the figure the pitch of the axis. The length of the arrow is proportional to the pitch. Vertical pitch is shown as a black spot with a circle around it.

A generally uniform orientation of all arrows representing deformation of more than 50 per cent is at once apparent. They point southeastward and remain approximately parallel throughout South Mountain fold. The regularity south of Waynesboro and between Chambersburg and Carlisle could hardly be more pronounced. In the southern portion all arrows point down dip of cleavage and parallel to the lineation in the volcanics in the center of the fold. Down-dip elongation is also prominent in the Chambersburg-Shippensburg area, and along the northern slope of the uplift east of Shippensburg, the trend of fold axes changes, but elongation direction does not.

Between Waynesboro and Scotland the folds which plunge into Hagerstown Valley become upright, the regular east pitch disappears, and oöids are discs in the vertical cleavage. The upward and forward movement of the South Mountain fold, which produced a steep and partly overturned limb in the southern and northern areas, is distributed over 3 folds and a much greater distance than in the other areas. Many specimens of this region are from crests of anticlines or synclinal centers, and horizontal bedding is common.

The west side of Hagerstown Valley syncline is unfortunately not well represented with oölite measurements. In the Clear Spring area, however, Conococheague limestone oölites appear and maximum elongation points toward the west and under the fault contact with the northern continuation of the Massanutten Mountain uplift. Here Silurian and Devonian sandstones and shales are faulted against the Cambrian Toward the north the fault dies out, the throw lessens and folds of the Mercersburg area expose Ordovician Martinsburg shale in the core of the rather large Cross Mountain anticline. Deformation is most intense and at the same time most strikingly oriented where tectonic disturbance is at a maximum culminating in faulting. Orientation of maximum elongation on both sides of Hagerstown Valley is down dip on the east and the west sides.

It is unfortunate that more measurements were not possible west of Mercersburg and Chambersburg, but suitable oölites seem to be lacking. The Beekmantown oölites at McConnelsburg are almost undeformed or siliceous.

Measurements of crinoid deformation may well substitute for cölites and are discussed below. Crinoids in the Martinsburg shale near the summit of Cross Mountain show elongation in a vertical plane and lateral (horizontal) reduction of circles. Maximum elongation seems to parallel the fold axis.

ORIENTATION IN FOLDS

Orientation of oöid axes a and c, bedding, and cleavage are shown in Figures 1–5 of Plate 12 for 74 localities.

Oöid orientation is without exception with a and b in the cleavage plane and with the shortest axis normal to it. Either axes may assume the direction of the fold axis, but as a rule a is normal to the fold axis. In Figures 1–5 of Plate 12 the longest axis parallel with cleavage dip is a maximum deformation axis; b is, as a rule, normal to the section shown.

Deformation axes show only accidental relations to bedding orientation. If cleavage parallels bedding, a and b are in the bedding plane as in Figure 3 of Plate 12, specimens 330 and 333, and in Figure 4 of Plate 12, specimen 258.

Where deformation is intense a lineation appears parallel to *a*, and in the South Mountain area a is down the dip of cleavage or nearly so. If cleavage is vertical as in symmetrical folds a is also vertical in the cleavage plane as for instance in number 392 and 399 of Figure 4 or 375 of Figure 5 of Plate 12. On Plate 10 several vertical axes can be seen near the Maryland-Pennsylvania border west of Waynesboro. Southeast of Chambersburg three arrows point northward and apparently parallel the strike of the fold axes. These arrows however are normal to southward-dipping fold axes. Steep axes at 70° or 80° are common in the Chambersburg-Greencastle-Waynesboro triangle and where upright folds and vertical or steep cleavages prevail.

Axial plane cleavage parallels the axial plane as a rule only in the vicinity of the axial plane. In the limbs of folds it deviates and forms a fan which opens toward the convex side of a fold,—that is upward in anticlines and downward in synclines. This is well shown in many Appalachian folds and has been observed frequently (Albert Heim, 1878; Leith, 1923, Fig. 47). Construction of Figure 8 would be impossible without a cleavage fan. Bedding and cleavage are in their mutual characteristic relative position in Figure 8. So characteristic is the relation between the two that knowledge of the shape permits the cleavage to be drawn; conversely, knowledge of the cleavage pattern would disclose the shape of the associated fold. Further, plotting of öolite elongation would disclose both the cleavage and the fold patterns.

Near South Mountain the overturned lower limb is exposed, hence the dip of cleavage and the pitch of elongation of cölites are gentler than in the valley (*see* also Figure 8).

Distribution of specimen numbers and oöids in Figure 8 shows that vertical or nearly vertical beds were sampled most frequently. Obviously the western slope of South Mountain exposes the vertical beds of an asymmetrical fold.

CHANGE OF VOLUME DURING DEFORMATION

In the calculations of deformation intensities the assumption was made that the volume remained constant because seemingly no material escaped or was added in the process. Since the proposition affects all conclusions so far as they are quantitative the author attempts to further analyze this point.

Several processes may result in volume changes: (1) crystallization, recrystallization, and replacement; (2) disruption of oöids and loss of parts during deformation; (3) compaction and loss of water.

In order to appraise the volume changes the average-sized unit sphere was plotted at an arbitrary scale (Fig. 10). Distortion ratios $\frac{a}{c}$ were then calculated and ellipses constructed with b = constant. The percentages in Figure 10 were chosen to represent some of the values observed frequently. Percentages have been calculated as extension of the unit sphere or $\frac{a}{r} \times 100$. This theoretical diagram shows the configuration to be expected with deformation without change of volume.

The measured values in Figure 11 differ from the theoretical diagram in many respects: The three highest percentages—85,100, and 125—are much smaller than the theoretical values. Unit sphere and ellipse are equal to the calculated values up to 58 per cent. From there on upward they are increasingly undersized.

Several possible reasons present themselves: Oöid substance may be lost with increase of deformation intensity; measurements may become less reliable particularly in the direction of maximum deformation when ends begin to fray as in Figure 2 of Plate 6, and Figure 5 of Plate 4. In Figure 11 the source material may have been of unequal size which explains the difference between the 10- and 23-per cent diagrams and their unit spheres. That difference would scarcely be as large as it is in the last

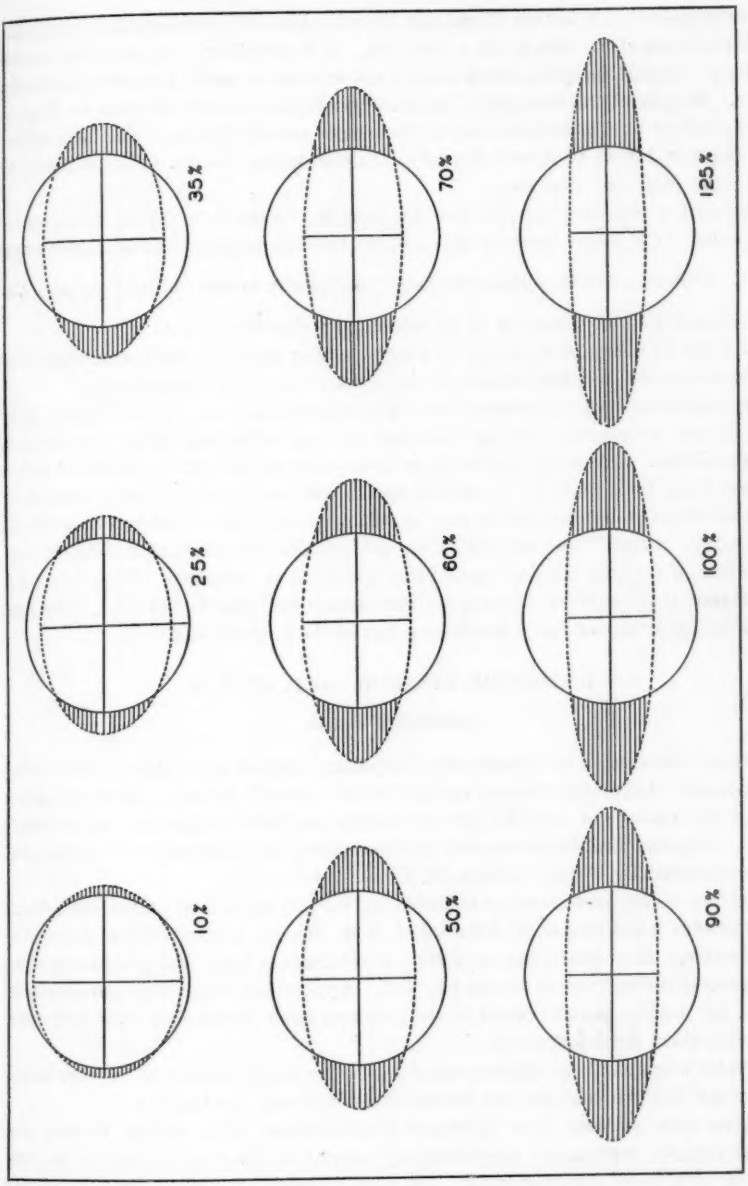


FIGURE 10.—*Geometrical solution of theoretical deformation*
In reference to one unit sphere for constant volume.

three examples. The author thinks that there is a loss of material and inaccuracy due to deformation of the ends in the a direction. It is advisable to use a section normal to the one shown, including the b and c axes, in order to verify the calculations of a and r. In spite of this inaccuracy, ratio and orientation remain the same for large or small oöids or unit spheres as long as the shapes remain similar. The large sphere and ellipse in Figure 10 show a 100 per cent deformation like the values in Figure 11 which are only half that size.

The author feels that the absolute size may not be decisive as long as values are computed as ratios or in percentages, and the third dimension b remains nearly constant. Distortion of b is fortunately small particularly in case of high $\frac{a}{c}$ ratios. Deformation of b (in the direction of the fold axes) is discussed below.

Loss due to compaction or loss of water tends to affect all oöids and matrix and would seem to be harmless because its value enters all calculations equally.

Crystallization and replacement are very common and can be seen in every slide. Due to ease of detection they are harmless as long as the original outlines of oöids remain visible. Almost all the long axes have grown as in Figure 1 of Plate 5 and in Figures 1 and 10 of Plate 8. Growth of aprons and rims does not always indicate increase of diameter because aprons grow as well in c as in a, even if the c axis has shrunk noticeably. Growth and crystallization are postdeformational and therefore only important if original textures have been destroyed or obscured. Even where the entire slide is crystallized, original outlines remain well visible, but thick slides may be necessary to detect the yellow-brown tint of the original oöid.

DISTORTION PARALLEL FOLD AXES (*b*)

GENERAL REMARKS

Foward movements on thrusts very frequently support or exaggerate the folding process, and theoretically there is no limit on the forward movement on thrust planes except the amount of material and the energy available to perform the necessary work. Far-travelled thrusts are well known and crustal shortening due to folding has been estimated by several authors (E. Cloos, 1941).

The fact of free movements in the cross section (*ac*) plane is so well recognized and obvious that it has frequently been taken to be the only kind worthy of mention or measurable. Most geologists are willing to conclude at sight that pressure or stress is normal to the fold axis in almost any fold. Arrows indicating major movements or forces are usually placed normal to the axes and cross sections are most frequently drawn to show the deformation.

In folds where cleavage appears, smaller or larger displacements on cleavage planes are normal to the fold axes or the intersection of cleavage and bedding.

Alpine cross sections show enormous displacements, rolls, decken, thrusts, and rather extreme movements approximately normal to the trend of folds. In comparison with these large distortions, the third dimension is little deformed and may at times be considered constant.

Deformation of *b* parallel to the axial trend has been described and discussed by

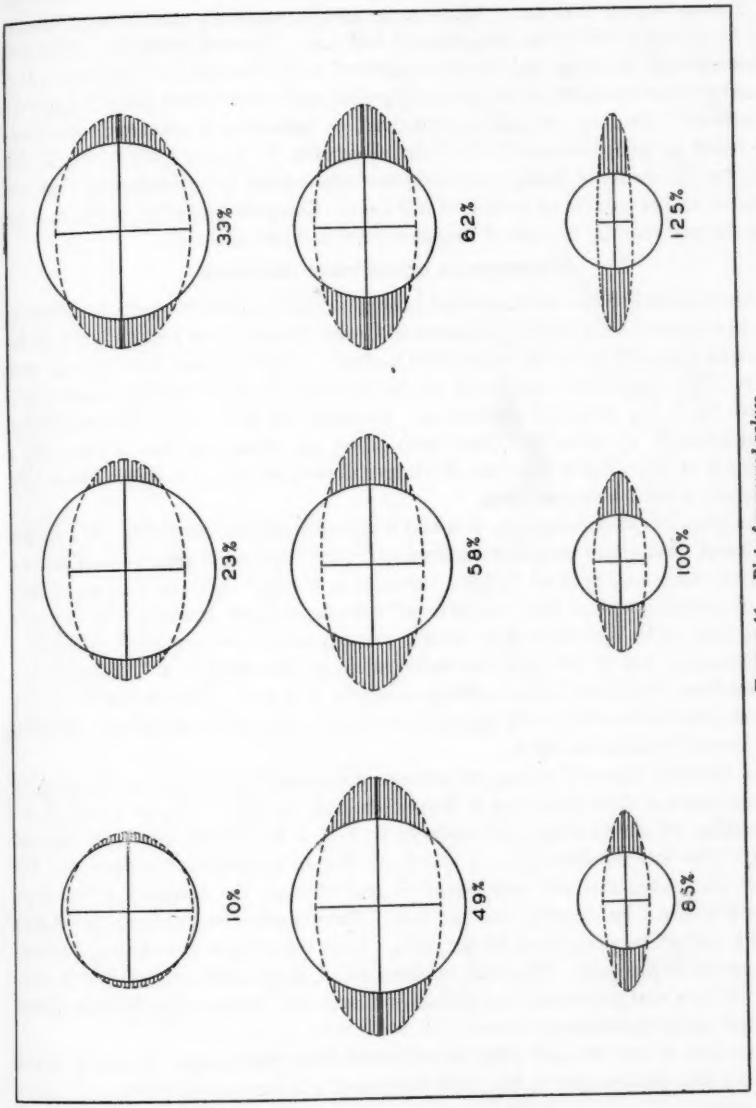


FIGURE 11.—*Plot of measured values*

For comparison with Figure 10. Third dimension neglected. The calculated unit sphere becomes very small beyond 70 per cent.

Albert Heim (1905, p. 4441) and Arnold Heim (1906), Sander (1912, p. 254) and many others. It is generally of a lesser order of magnitude than deformation in *ac*, but it is an important factor. Arcuation as seen on maps, like the Appalachian arc, may be accompanied by an elongation of fold axes. Upward arcuation of fold axes as revealed by plunging folds is also associated with stretching of fold axes. Horizontal and vertical pictures are interchangeable, and related cross joints fan upward or outward. Doming of uplifts, intrusives, or subordinate movement directions also result in such distortion in the third dimension (E. Cloos, 1946, p. 12, 28, 30).

In the discussion of linear structures two orientations have frequently been emphasized; either parallel or normal to fold axes. Elongation parallel to fold axes has been stressed recently because of its significance in fabric analyses.

DETERMINATION OF THE THIRD DIMENSION

Deformation in *b* can be determined in longitudinal sections or on maps and locally by observation of distortion of bodies of known shape. The author has here determined *b* at 119 localities where two mutually perpendicular thin sections were made. The values were calculated also in per cent of extension of the unit sphere. Figure 12 is the graphical evaluation. Deformation in *b* is shown horizontally, deformation in *a* vertically. Since both scales are equal, the line representing *a* equal *b* is at 45°. Below that line, *b* is larger than *a*, above it *a* is larger than *b*. At 15 localities the 2 axes are equal.

The amounts of deformation in *a* and *b* are mutually independent. The author had feared that errors may have entered and would appear as proportional increase of deformation in *a* or that in high values of a, b might decrease because of inaccurate measurements. Any proportional interdependence between the two axes would have to be investigated for errors. Eighty-seven per cent of all values for *b* are between 0 and 10 per cent and independent of distortion in *a*. Three *b* values are less than 10 per cent in spite of high values for *a* of more than 100 per cent. The highest deformation for *b* is 32 per cent and in the two cases *a* equals *b*. The oöids were merely flattened to discs.

The insert of Figure 12 shows percentages of deformation in *b* plotted horizontally and the number of observations is shown vertically as bars. The graph shows the summation of observations as intervals: 0, 1–5, 6–10, 11–15, 16–20, 21–25, and 26–30. The low numbers at 1, 2, and 3 are due to computation procedure. The author considered one per cent equal to zero because the accuracy of measurements is within 5, but scarcely one per cent. Twenty-six values are zero, 24 between 1 and 5, and 29 between 6 and 10 per cent. From there the values drop and remain low beyond 20 per cent. The peak between 6 and 10 per cent is significant because it points to a real maximum and probably means that deformation is three dimensional at many localities.

In an area of this size and with the rather intricate arrangement of axes it can be expected that deformation in the third dimension will vary considerably.

REGIONAL ARRANGEMENT

The (b = *b*) axes were platted on Plate 11, and an attempt was made to compare these with field measurements and to study possible relations between pitch and deformation intensities.

Plate 11 shows the intersections of cleavage and bedding, measured *b* axes, and fold axes. Double arrows are horizontal axes. Where *b* is horizontal, the *ac* plane is vertical and therefore normal to the axial trend.

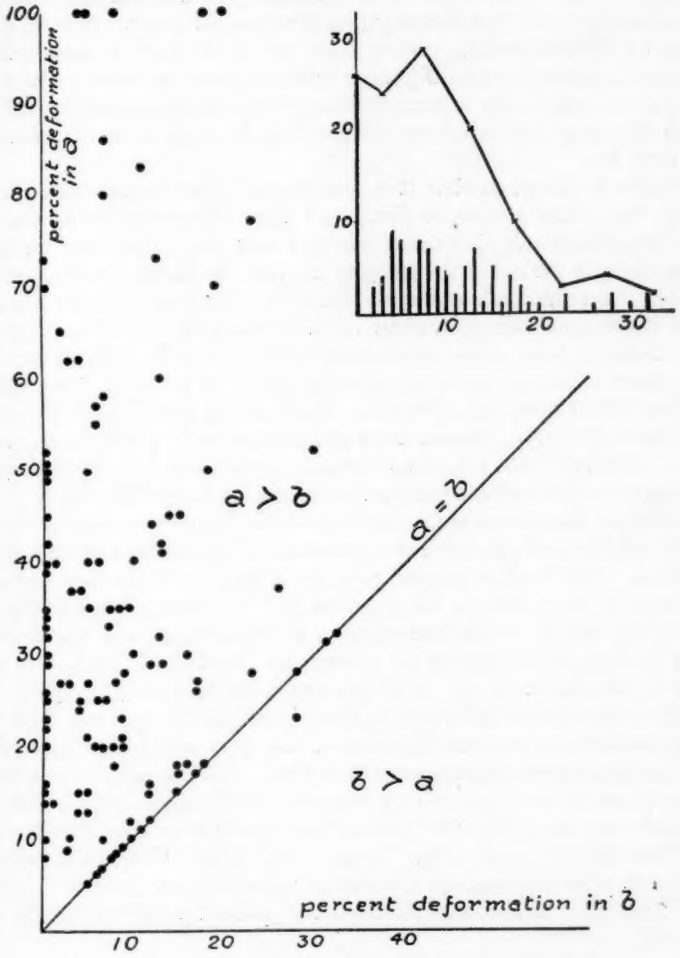


FIGURE 12.—*Deformation of* b *axes in relation to deformation in* a
Insert: number of measurements shown as bars.

This trend is constantly northnortheast and northeast in spite of arcuation of South Mountain. Between the Potomac River and Waynesboro the axes parallel the large fold and uplift to the east and remain essentially horizontal. In the vicinity of Waynesboro and to the north, axes pitch south-southwest or are horizontal, and at Stonehenge near Chambersburg the directions are confused and deviated at the

southwest end of a plunging fold. From here to the northeast, the trend is to the northeast. South of Newville and Carlisle the northeast trend continues, and the axes dip off South Mountain.

Little of the curvature of the South Mountain fold is accomplished by curving axes, but mostly by en echelon arrangement of subparallel trends. Between Waynesboro and Chambersburg the western boundary of the uplift is north-south, but accomplished by southwestward pitching folds with constant strike. The northern portion of the uplift seems to have advanced further northwestward by addition of at least three large folds which are well shown in the trend of the Waynesboro formation (Pl. 11).

Intensities are shown on Plate 11 in large figures. Near Keedysville there is considerable but rather irregularly distributed three-dimensional deformation. Between Waynesboro and Greencastle the fold axes are undistorted; southeast of Chambersburg at the end of the plunging fold near Stonehenge deformation is considerable. Near Shippensburg there is little or no distortion, and from here on east there is always some elongation where the axes plunge off the northern slope of the uplift. Here the larger values are at greater distance from the uplift than the lower ones. South of Carlisle, the values decrease from 17 to 13, south of Newville from 6 to 2, and 12 to 4 toward the Mountain. Whether this distribution is significant or accidental is uncertain. More detailed information may provide a more complete picture. Near Smithville the values increase eastward, and in the southern portion they seem to increase east and westward from a central zone of low values.

The irregular distribution of intensities shows that the lineation parallel to *b* cannot very well be due to elongation of fold axes due to intense deformation in the folding process. The linear structures, presence or absence of cleavage, or intensity of folding show no relation to the distortion in *b*. In such a large, uniform, and asymmetrical fold the author had expected to find a much more intense and uniformly distributed distortion in the subordinate direction (E. Cloos, 1946, p. 12).

Lack of deformation is very significant and shows that lineation in *b* is due to intersecting shear planes rather than elongation especially in the areas of low values over a wide area with recognizedly intense deformation as shown by asymmetry of folds, cleavage, intense lineations, and thrusting. This may mean that elongation of *b* may generally be low also in very intensely deformed areas. The author thinks that this determination shows for instance that pebbles of extreme distortion values as described by Goldschmidt (1916), Strand (1945), Kvale (1945) and others, cannot be the result of stretching in the direction of fold axes due to movement normal to them. The author has recently discussed this problem at some length (E. Cloos, 1946, p. 30).

ELONGATION OF b IN ARCUATION

The existence of regions without elongation in the direction of the fold axes indicates that Appalachian arcuation is not entirely the result of bending of an originally straight line into a curve. It also illustrates that the larger forward surge of folds in the center of the arc may be accomplished without intense stretching. The outer portions of an arcuated orogen should show larger elongation of *b* than the

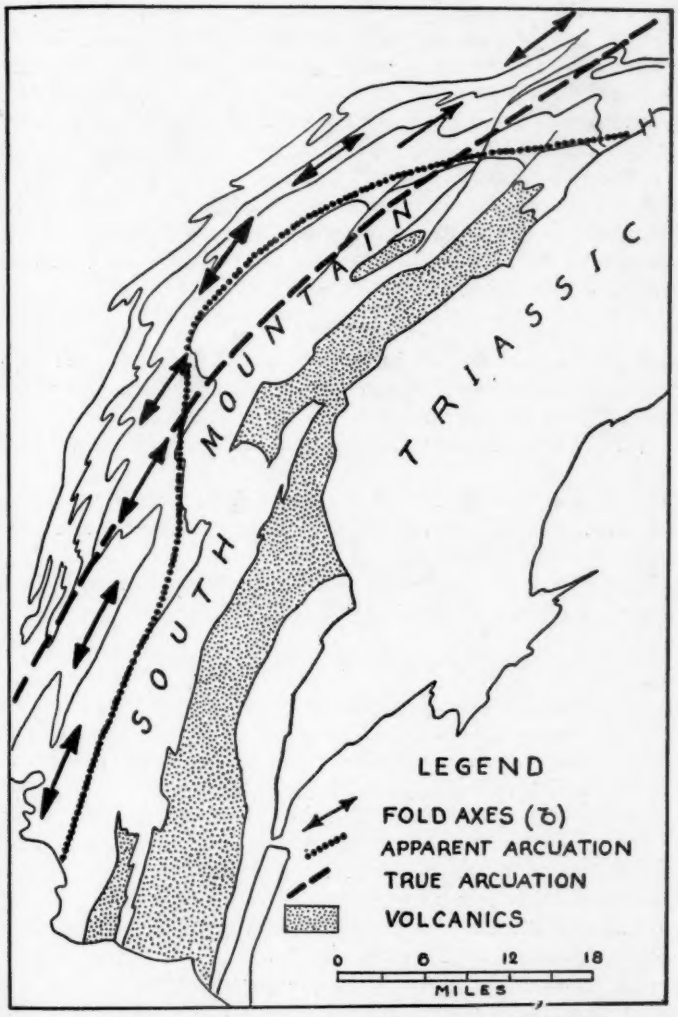


FIGURE 13.—*Apparent and true arcuation of South Mountain fold*

inner ones. The author knows of no systematic investigation of this question but feels that it would be most fruitful to measure deformation in *b* at many points in an arcuated orogen as the Appalachians, the Jura, or the Alps. Such a study may throw much light on the order of magnitude of lateral movement because folding would have to be radially outward with constantly increasing distances between points along the strike of the axes. The amount of increase will then be an indication of divergence and also arcuation.

Application of this principle to the present area is shown in Figure 13. A rough outline copied from the State maps of Pennsylvania and Maryland (1933) shows the apparent arcuation of the area as seen physiographically and in the trend of the formations. If the fold axes are plotted and folds traced, however, they show that the forward bulge is produced by a number of additional folds in the northern half of the map area and that the axes plunge off the uplift southwest and northeastward.

The remaining arcuation is probably due to varying folding intensity and the number of folds that account for the lateral shortening. The rather small elongation of fold axes seems to indicate absence of true arcuation of a larger order of magnitude. Such extension as has been described by Albert Heim (1921) in the Jura is lacking. There, diagonal faults increase the extension of the orogen.

SUMMARY

The third dimension should not be neglected since it can be a rather large factor. In the South Mountain area there is no large-scale and uniform elongation parallel to the trend of folds, but there is considerable local extension.

Extension in *b* is unrelated to extension in *a*, and neither value is related to the axial plunge.

The absence of uniform axial extension shows that the linear structures paralleling fold axes are not due to stretching and that the very intense lineation parallel *a* is due to movements in that direction.

Actual arcuation in the area is smaller than apparent arcuation. The limits of South Mountain fold are determined by en echelon folds.

DEFORMATION OF CRINOID STEMS

The present investigation can be expanded considerably by using crinoids in shales and other noncölitic sediments. The discs of a crinoid stem fall flat into a bedding plane upon disintegration of the stems, but whole stems will, if deposited in a bedding plane, lie with the discs normal to the bedding planes. Two directions of deformation can thus be readily preserved, one within the bedding and the other normal to it. Oblique directions will appear only as components. If a search is made for stems in favorable positions it is still possible to detect the deformation directions and intensities. A stem that happens to be parallel to the intersection of bedding and cleavage will, even in the limb of the fold, register the total maximum deformation in the cleavage plane but at an angle to bedding.

Figure 14 illustrates the possibilities which permit easy determination of deformation axes a, b, and c. The top figure, A, is a perspective block with one disc parallel to bedding cut by cleavage normal to it, a stem parallel to cleavage and bedding intersection, and another one normal to cleavage and intersection but within the bedding plane. Cleavage is vertical; deformation is within the cleavage plane. Discs in the bedding are flattened normal to cleavage and elongated parallel to it. The stem is also elliptical within the cleavage but vertical. The deformation illustrated indicates approximately that a equals b. The stem is as elongated as the disc and also higher than normal which would also thicken the disc. The stem normal to b is shorter, but larger in diameter. If many stems and discs are available a good value

can be computed for a, b, and c and referred to the three mutually perpendicular axes and planes.

The position of bedding is most important and illustrated in Figures 14 B-G. Figure 14 B, C, and D are the three sides of the block A, forming a cube with hor-

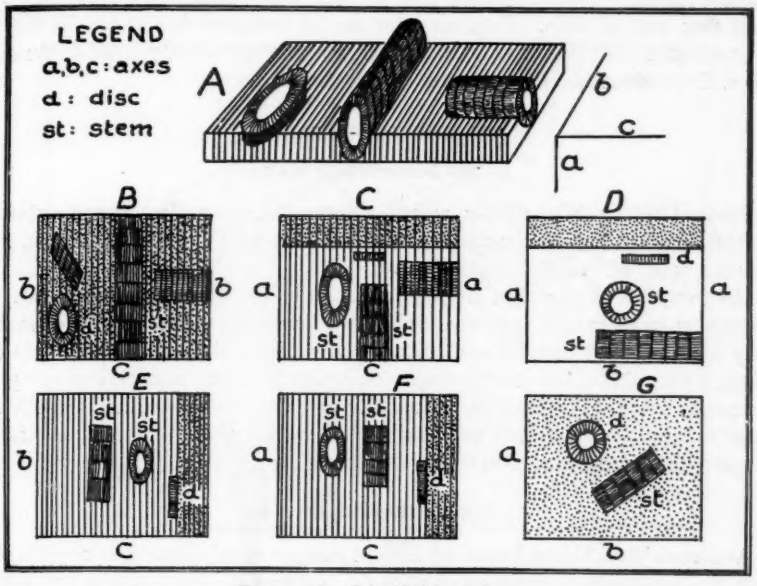


FIGURE 14.—*Crinoid deformation*

A: Block diagram. abc: co-ordinates. B, C, and D: views from three sides of the above block. E, F, and G: views from the same side but with vertical bedding.

izontal bedding and vertical cleavage representing the situation below the summit of Cross Mountain, Pa. Figure 14 B is the top view of A and within the bc plane. C is the cross section, normal to the intersection of cleavage and bedding. A vertical stem and a horizontal disc parallel to the bedding are flattened laterally; a horizontal stem is shortened and thickened. A view of the cleavage plane (D) shows no cleavage, but bedding, and undeformed but over-sized discs, which may be stems at depth. The stem at the bottom is elongated from left to right and heightened vertically, but both deformations cannot be seen in this section. Figures 14 E-G show essentially the same arrangement of forms, but vertical bedding and cleavage are mutually parallel. E is the top view; bedding is vertical. The disc of Figure 14 B has disappeared, but a stem parallel to bedding may show the distortion. A disc in the bedding plane would merely show its side. F is a cross section with the two stems of E but opposite sections. The disc is still seen only from its side. The ab section, G, is a view of bedding and cleavage showing no distortion of discs but enlargement which is detected only by comparison with other sections.

Oblique cuts will also permit determination, but calculations become more compli-

cated, and assumptions will have to be made as to the position of the cut to the deformation axes. Evidence available so far has shown that maximum axes are closely related to the cleavage-bedding intersection and fold axes. It is worth searching for crests and flanks of folds for maximum information.

Since crinoid stems are common they are very useful, and their sizes are less variable than that of oöids. They are more readily compared but do not furnish the three-dimensional picture in one specimen. An excellent locality is below the summit of Cross Mountain, Pa., along the road to the fire tower.

DEFORMATION ANALYSIS

THE DEFORMATION PLAN

Sander (1930, p. 57) described several deformation plans ("movement pictures", Knopf, 1938, p. 26) and studied their symmetries, for the deformation plan may reflect a setup of forces.

However, not all plans are directly indicative of the movement picture, and the author has recently tried to emphasize that the movement picture may be correlated only indirectly and through subordinate movements with principal directions (E. Cloos, 1946, p. 22). It is therefore most important to include an area large enough to comprise subordinate as well as principal movements. A thin section is mostly too small to show the whole plan, and detailed field work is always necessary in order to properly place the thin section within the master plan.

THE SOUTH MOUNTAIN PLAN

As seen in Plate 11 and Figure 15 the fold axes are largely horizontal or pitch very gently. Maximum deformation of oöids (a) is normal to the fold axes and pitches southeast where folds are overturned to the northwest (Pl. 9). a is a megascopical lineation, whose intensity and visibility also grows with intensity of deformation. The cleavage plane is determined by a and b without exception. Cleavage also grows more conspicuous with increasing deformation intensity. Bedding is transected by cleavage, and their intersection always parallels the fold axes. The deformed oöids are strictly correlated to this plan. The maximum axes a parallels co-ordinate ***a***, the mean axis b is coordinate *b* (also *B*), and c is normal to the *ab* plane, which is at the same time the cleavage plane. Symmetry is monoclinic with the ac (and *ac*) plane as symmetry plane.

Figure 15 shows the axial part of an overturned fold as found along the western slope of the Mountain. The mutual positions of structure elements is constant in a large area, and the only variation is in the orientation of all elements in space. In upright folds cleavage is vertical or nearly so, and the bedding is horizontal in the crest.

The deformation is accompanied by rotation of bedding into a vertical position. This rotation may be flexure or slippage on subparallel planes and subsequent shearing. Rolling and rotation are absent as indicated by the regular subparallel arrangement of elongate oöids, whose positions remained unchanged since early deformation.

LINEATION AND CLEAVAGE

Lineation has been discussed recently at some length (E. Cloos, 1946) and is very prominent in the entire South Mountain fold.

Parallelism of oöid extension and lineation permits quick orientation in the field and facilitates choice of section for sawing and thin sections. Even the more massive

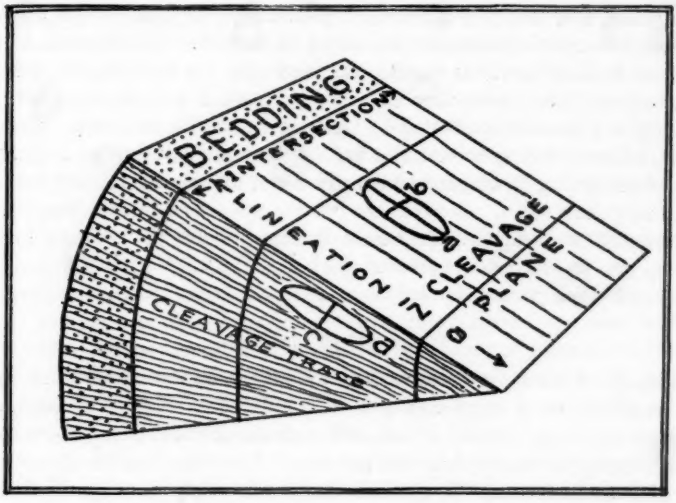


FIGURE 15.—*Deformation plan in South Mountain*
Axial portion of overturned fold showing mutual relations of bedding, cleavage, oöid extension, and lineation.

lower Cambrian quartzites show streaks, lines, clusters of magnetite, and stretched pyrite, and under the microscope quartz needles in *a* as described by Fellows (1943).

The volcanics in the core of the uplift are also strongly lineated. Cleavage planes are covered with chlorite blebs about 1 or 2 inches long, ¼ or ½ inches wide, and paper thin. In the more massive greenstones amygdaloidal cavities or deep-green epidote hornblende or chlorite blebs are very common and also well oriented. The author has called attention to this structure repeatedly (E. Cloos, 1940, p. 866, fig. 8A; Cloos and Hietanen, 1941, Pl. 8; 1946, Pl. 2).

Maximum elongation of oöids is lineation in *a* and without exception normal to *b* (*B*) and the fold axes.

A second pronounced lineation parallels the intersection of bedding and cleavage and the fold axes *b* (*B*).

Cleavage is absent where deformation is feeble and grows stronger with increasing deformation. Approaching South Mountain, cleavage and lineation appear first as mere cöid orientation which intensifies southeastward. It is possible to identify the deformation plan in the orientation of oöids long before cleavage or lineation become megascopically visible.

In the oölites and associated Paleozoic rocks cleavage and lineation mark stages in

a progressively more intense deformation of soft or maybe unconsolidated rocks. Limestones were formed under strain of varying intensity, and, as shown by the microscopic picture, cöids were deformed according to a uniform tectonic plan and pattern before crystallization of the matrix. Tectonites formed before rocks.

Oöid deformation may be compared with formation of flow structure in igneous rocks. Here constituents were arranged in patterns prior to consolidation during a viscous phase, and therefore a normal crystallization sequence exists without deformation, but with orientations in various intensities. Synkinematic intrusions furnish the most intensely textured rocks, and they are hard to distinguish from metamorphics. The oölites may be compared with a synkinematic intrusion of which only a portion was affected by deformation during intrusion. At one end there are primary flow structures and an undisturbed crystallization sequence. At the other end strong cleavages and lineations and intense deformation seem to indicate a crystalline schist. Between the two are gradations, but the whole intrusive shows one deformation plan. Intensely deformed oölites are schistose rocks, but carbonate growth and pebbles are undisturbed. The undeformed oölite shows the same crystallization phenomena, but there are fossils and no cleavage or lineation in *a*.

DISCUSSION OF CLEAVAGE

Definitions.—Cleavage as here used is the planar discontinuity which is defined by the position of the a and b axes of the ellipsoidal oöids, whether visible in slightly or strongly deformed cölites. It coincides with the *ab* plane of the co-ordinate system, and its dip fluctuates about the fold axis. Its strike parallels the axial trends where axes are horizontal. It also contains the lineation in a (*a*). Finally c = *c* is normal to this cleavage. Where oöids are only slightly deformed this cleavage remains invisible.

Near the axial plane of folds, cleavage is parallel to it and thus becomes axial plane cleavage. Since it is due to flowage it may also be called a flow cleavage.

The cleavage is therefore a secondary *s*-plane parallel to ab = *ab* and interesecting a primary bedding-*s* (depositional *s*) in *b* (fold axis). It grades from an incipient latent stage through faint visibility into a very prominent and dominating structure which obliterates bedding and leads geologists to believe it were bedding. In all its stages it maintains constant relationship to all other structure elements within the deformation plan (Fig. 15).

Cleavage interpretation.—A very useful summary and discussion of cleavage theories has been presented by Turner (1936; 1942). A more complete but more intricate discussion is by Sander (1930).

A review of cleavage theories shows that the discussion focuses on the question whether the cleavage, schistosity, or foliation formed as a shear plane at an angle to the major extension or strain, or in the plane including the major and mean strain axes.

One major difficulty in the interpretation of cleavage as shear plane is the one-sidedness of most cleavages where there should be two shear planes in intersecting directions. This difficulty may be overcome in rotational deformation in which the two directions rotate at unequal rate, thus producing deformation of different kinds,

possibly flow and fracture cleavage. This would require that the two cleavages, if correlated intersect in *b* (*B*).

The cöids were spherical at the beginning and have become ellipsoidal due to deformation which is clearly related to the folding of South Mountain and the Appalachian in general. Crystalization is later and adds to the visibility of the orientation. Cleavage forms in the AB plane of Becker's strain ellipsoid and not in a shearing direction.

This possibility has been discussed by Sander (1930, p. 79) for material of "very low rigidity" as for instance a dough which is deformed by its weight or for viscous liquids. In this case the strain ellispoids become so flat that their circular sections almost coincide with the AB plane equal *ab*. The cleavage plane then becomes *ab*. Becker's strain tectonics may be less applicable than the idea of tectonic flow (*tektonisches Strömen*) and that nonrigid bodies be preferably analyzed by application of the mechanics of viscous flow.

Cleavage in the South Mountain fold is under these premises due to laminar flow in flow planes (ab=*ab*), and the lineation is a cylindrical flow in flow lines.

Within the asymmetrical fold the cleavage (and ab planes) dip toward the center of the fold, and cleavage as well as lineation grow more intense in the same direction. If intensity of a deformation is proportional to the amount of (distance) movement that took place, maximum intensity is then located near the center of the large fold where movements must have been larger because the distance from the horizontal to the crest of an asymmetrical fold is larger than to the flanks.

Oöid extension by laminar flow at a soft stage would rule out the possibility of a flexure fold. The implication of this conslusion in thickening and thinning of stratigraphic sections is discussed below.

OÖIDS AS STRAIN ELLIPSOIDS

Limitations.—Application of the strain ellipsoid is confined (1) to the realm of Hooke's law, (2) to small homogeneous bodies, (3) to homogeneous stress, and (4) to homogeneous strain.

Hooke's law merely expresses the fact that unit stress is proportional to unit strain or that the deformation is within the confinement of the elastic limit. In a homogeneous body physical properties are equal in all directions. Homogeneous stress is stress that does not vary in intensity or direction within the affected area. Homogeneous strain is strain whereby configurations that were similar before strain remain similar. It is obvious that these conditions are most readily met with in an infinitely small area.

The most frequently found geologic inhomogeneous deformation is a fold.

All applications of the strain ellipsoid to geologic units and objects grow more inaccurate, more schematic, and more unnatural and awkward-looking as they include larger areas. The over-application of the strain ellipsoid theory especially without statement of basic assumptions does not encourage precise observation or analysis by students. In addition, its use is dangerous because the student who finds his problems solved stops thinking. Very excellent limiting statements are found in the textbooks by Hills (1941, p. 20–28) and Nevin (1942, p. 24).

Oöids.—Deformed oöids are not strain ellipsoids because they are inhomogeneous, deformed plastically, and beyond the elastic limit. They are mere designs like fossils or other bodies that have been distorted. Deformation was neither homogenous nor by homogeneous stress.

Their usefulness lies in the records of distortion which they preserve and in the flowage directions they indicate. Their rigid position in the deformation plan makes reconstruction possible for many points of an area. They are of little help in analysis of rupture because they represent only very small areas and change positions within one fold, whereas ruptures transect entire folds.

The oöids are useful only as long as they are not expected to furnish more information than they are able to provide.

FRACTURES

The South Mountain area is well jointed, and several directions are very conspicuous in the field. In the dark limestones joints are generally filled with fresh calcite and stand out well. In the quartzites joints appear as open fractures and determine the shapes of boulders and cliffs. The volcanics are also well jointed and surfaces are frequently covered with epidote and other secondary minerals.

A study of intersecting joints and their mineralization in thin sections permits dating deformation in terms of oöid distortion and flowage.

Oöid distortion is very early and followed by crystallization and growth of matrix radially on distorted cöids. Tectonic fractures formed after consolidation had progressed far enough to permit smooth, even, and transecting joints with clean sharp walls. They cannot always be traced far but are offset repeatedly en echelon. Within one slide joints may be offset repeatedly.

Crystallization has filled all fractures in limestone and preserved them as thin white lines which can be found in all clean exposures. Calcite in joints is generally untwinned, very clean, and the grains are larger than in the matrix (*see* Figures 5 and 14 of Plate 8, and Figure 5 of Plate 4).

Tension joints normal to fold axes or lineation and fractures at an angle that is bisected by the fold axis and lineation in *a* are common directions. There are therefore six directions, and each may show secondary and small fractures in associated directions of feather joints.

Tension joints normal to the *b* axes (*ac* joints) are largely vertical or dip steeply and strike northwest slightly converging southeastward as fold axes bend from northnortheast near the Potomac River to northeast near Carlisle. As the axes pitch, the joints are tilted also. There must have been slight displacements during formation of the fractures since they are very commonly accompanied by feather joint zones (E. Cloos, 1932). These zones are about 2 inches wide, can be traced 10 to 20 feet along their strike, and fade out as others begin. Their spacing along axial strike varies, but there are some zones in almost every exposure of any size. The average distance may be one zone for every 6 to 10 feet. The displacement is about a half inch to an inch (Fig. 16).

Large cross faults which may be expected and should be present in large numbers have not been found.

The same direction has been noticed in thin sections, but not many specimen show it because in sampling, fractures and fracture zones were deliberately avoided. Where present they are always "open", that is they tend to be wide and filled with clean, large carbonate crystals, untwinned, and with a tendency to grow inward from the walls in larger grains.

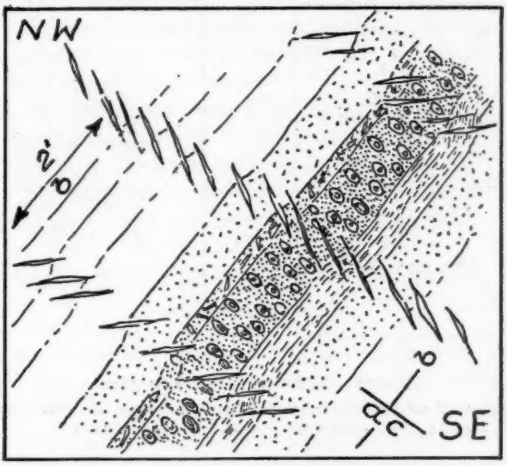


FIGURE 16.—*Fracture zones normal to fold axes*

Horizontal view in the direction of tension joints and indicated by feather joints. Co-ordinates: *b* equal fold axis; *ac* normal to *b*.

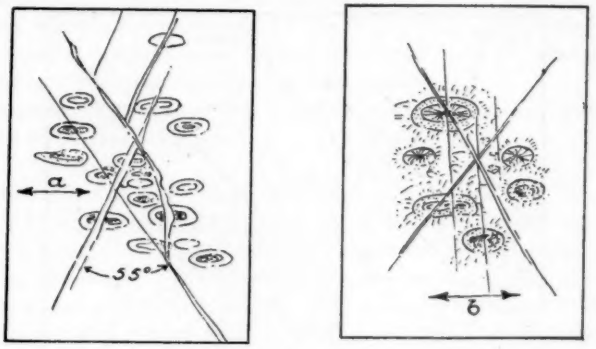
Tension joints normal to lineation in *a* are also common but always very much smaller and limited to regions with intense lineation. These are *bc* joints in response to elongation in *a* and appear in the field as strike joints, parallel to axes but dipping mostly northwestward about normal to the lineation. They are shown in Figure 17 B with shear fractures intersecting in *a*.

Shear fractures are also common but rarely as large and smooth as cross joints. They are much less evident in the field, and in thin section may be identified by their angular relation with oöid axes because they tend to show only as fine white lines and are, also, commonly not filled with clear calcite but with mylonitic debris and fine sharp grit. These fractures are associated with elongation parallel to *b* or *a*. Where oöids, fold axes, or lineation are present identification is easy, but they are otherwise hard to find, particularly since they do not dominate in outcrops. Figure 17 A shows a set of shear fractures intersecting in *b* and at angles of approximately 62° to the maximum oöid axis *a*. The angle between fractures is 55°. The major fracture in the lower right-hand quadrant vanishes to the northwest, and a new and parallel one opens a little further up.

A similar arrangement but in a different orientation is shown in Figure 17 B. The angles are nearly the same, and it would almost be possible to mutually substitute the two drawings. The axis of the oölites is here distorted 18 per cent, the

b axis 8 per cent. In Figure 17 A the a axis is elongated 50 per cent and the b axis only 5.

The author tried to analyze the occurrence of these fractures in terms of elongation either in *a* or *b*. Distortion was compared with angles, and the number of slides showing different arrangements were plotted against deformation percentage of



A B

FIGURE 17.—*Fractures in thin sections*

A: shear joints at angle of 55° symmetrically arranged with respect to *a* axis. B: shear fractures symmetrically arranged with *b* (fold axis) bisecting. Small and fine dark lines are cross joints (tension).

corresponding axes. The number of slides showing good fractures is too small, however, and the available ones show no relationship, but an overwhelming number of cross joints (*ac*) are normal to fold axes.

The angle between shear fractures is always less than 90° and fluctuates about 60° in all oölites and all stages of deformation. This shows that distortion by flowage had no influence on the later deformation which seems to be determined by the physical properties of postflowage phases and by the degree of consolidation which was achieved at the time of fracturing.

The fractures formed in close relationship to the elliptical oöids, and their orientation is obviously dominated by the same tectonic deformation plan but in a later phase. Therefore consolidation had not progressed far enough to prevent flowage during oöid distortion but far enough to permit fracturing at a time when the plan which governed oöid distortion was still in effect. Consolidation must therefore have taken place during and between these stages.

CROSSED LINEATIONS

Influenced largely by the study of fabrics some authors have concluded that lineations like rodding, pebble elongation, and even linear flow structures indicate movements normal to these lineations. The author has discussed these lineations recently in a review of the lineation problem (E. Cloos, 1946). The present maximum elongation of oöids and gradation and combination of the axis of elongation with a very pronounced lineation affecting all rocks beyond the boundaries of the oölites

resembles the rodding in the Scottish Highlands, the elongate pebbles of the Scandinavian Highlands or other down-dip lineations.

The strong lineation here described needs some [illegible]on in the light of these interpretations. Maximum oöid distortion parallel *a* is the earliest direction visible in the oölites. This direction is intimately related to the folds and their axes and to the plan as it prevailed during deformation of the whole area. Extension in *a* is flowage normal to the fold axes and leads to formation of cleavage as axial plane cleavage near the axial plane. This plan includes also the core of the uplift and probably a fair portion of the Appalachians.

There is no evidence for a second phase of folding parallel to the axes of the larger fold with a resulting trend normal to the trend of *b* axes. There is also no room for such phase in the crystallization picture as shown by thin sections. The deformation plan demonstrated here was in effect from the beginning of folding to the latest stage of fracturing, and no other plan is evident at any other time.

ANALYSIS OF THE SOUTH MOUNTAIN FOLD

GENERAL REMARKS

Shear folds are not discussed widely and have not found much room in modern textbooks. They are, for instance, not mentioned by Leith (1923), Bailey Willis and Robin Willis (1934), Nevin (1942), or Forrester (1946) as important mechanism in folding. According to most texts, folds are merely bent strata.

Billings (1942, p. 90, Fig. 78) discusses shear folding as a form of fracturing and particularly as continuation of flexure folding. In his laboratory exercises Billings shows examples of flexure folds and their construction but not of shear folds.

Other discussions are in Hills' (1941) text where shear folds and their combination with flexural slip folds are shown (p. 82, 85), by Sander (1930, p. 260–261), Knopf and Ingerson (1938, p. 151), Hans Cloos (1936, p. 205), and others. Only few and isolated examples are given, and one gains the impression that shear folds are of more theoretical than practical interest.

Shear folds are, however, much more common than generally recognized and demand a different construction in cross sections than flexure and concentric folds. Determination of the depth to the crest of an anticline, the position of the crest below the surface in respect to surface exposures, and the position of the axial plane depend on the type of fold.

Shear folds cannot be dismissed as technicalities, unnecessary detail, or too rare because they are common in Alpine territories and their oil-bearing margins, as well as in the Appalachians. They are common in all terraines where flowage occurred. Cleavage may indicate the presence of shear folds.

Shear folds are probably more common in folding of unconsolidated rocks and deformation by means of laminar flow since subparallel glide or flow planes must be available. They are thus not to be expected in folding of consolidated beds unless deformation reaches the state of rock flowage and is accompanied by recrystallization.

Since folding prior to consolidation has received little attention laminar flow as indicated in closely-spaced cleavage planes may also have rarely been recognized.

Thickening of crestal parts of a fold is well known but is not often explained as the result of shearing.

A more detailed analysis of the condition of sediments at the beginning of folding may well uncover much evidence for shearing as an important mechanism of folding.

In the following an attempt has been made to outline the principles briefly and then to apply them to the South Mountain fold.

THEORETICAL PREVIEW

A bed or foliation may be folded by bending, shearing, or flowage. Bending tends to produce folds in which thicknesses of beds may remain unchanged normal to the bedding plane (Fig. 18). Such folds are concentric and constructed with a compass from dips in reference to one or several centers as shown by Billings (1942, p. 426, Fig. 32) and Busk (1929). Appalachian folds are generally drawn as of this kind (Willis, 1893; Stose, 1909; Butts, 1933; E. Cloos and Hietanen, 1941; and many others). A beautiful and often-pictured example is at Roundtop, Maryland. Not many folds are that simple; crests are usually thickened and, limbs thinned either by transport of material or by shearing and flowage.

Flow planes control the deformation and guide distortion in Figure 18 B. The parallel sections aa, bb, cc, and dd are displaced to a′a′, b′b′, c′c′, and d′d′ and their lengths remained unchanged. These are cleavage planes, and the movement is a slip in the direction of the cleavage. Such deformation is usually illustrated by comparison with a stack of cards that slides sideways (Billings, 1942, p. 90, Fig. 78). In Figure 18 B, all the dimensions of the original bed are changed, and the original thickness is not preserved anywhere. If this fold had begun as a flexure fold and subsequently been intensified by shearing, the shear planes may have formed normal to bedding in the crest, and thicknesses may then have been preserved parallel to cleavage and axial plane.

Reconstruction would therefore have to aim at restoration of a horizontal bed and at measurement of the thickness normal to the restored bedding plane. It would be essential to establish the fact that the fold is a pure shear fold without additional flowage as described below.

A shear fold with additional flowage is shown in Figure 18 C. This kind of fold is very common in all terraines where rocks were plastic. Comparison with Figure 18 B shows that in addition to slippage on aa, bb, cc, dd, a circle has changed into an ellipse by flowage. Oöids would have become ellipsoids, and thickening of the crest is accompanied by reduction of the dimension normal to cleavage (c). a has grown larger, b is assumed constant, and c is appreciably reduced.

There is no area where the thickness of the original bed can be measured, and reconstruction has to proceed in two stages: (1) the ellipsoid has to be reconverted into a sphere and (2) the pieces have to be slipped back into their original position.

The first step consists in calculation of the diameter of the unit sphere from measured values (cöids, pebbles, crinoids, spots, amygdules, *etc.*). This will provide the increase of c and reduction of a. A rough assumption will provide a level at which the once horizontal bed may have been relative to the others, and the pieces a′a′,

FIGURE 18.—*Types of folds*

A: Diagram of flexure fold. Flexing is accompanied by slippage on bedding planes, and thicknesses are constant normal to bedding. If fold is referable to one center, the fold is parallel; if there are several centers it is similar. B: Simple shear fold due to slipping on subparallel shear or flow planes. aa, bb, cc, dd, are constant but do not represent thicknesses of sediments in the fold. There is no center of curvature. C: Shear fold with flowage. aa, bb, cc, dd have not only slipped but are also moved closer together due to ellipsoid distortion. Measurements of thicknesses are impossible without reconstruction. D: Flowage component of Figure 18 C.

b′b′, c′c′, and d′d′ can then be moved back into their original position aa, bb, cc, dd. The thickness of the bed can then be measured normal to the bedding plane. This fold is the most common type and most frequently met with in crystalline terraines.

The percentages in Figure 18 C are assumed and have been chosen to resemble the South Mountain fold. Figure 18 D shows the flowage component without slippage on shear planes. When added to Figure 18 B the fold, in Figure 18 C results.

The curvature of a fold is determined by the distribution of extensions and slippage in different parts of the fold. It would be a most interesting and worthwhile project to study such folds, to determine the two factors systematically, and to attempt the reconstruction of pre-deformation conditions on this basis. As far as the author knows no such studies have been attempted.

Deformation of beds into folds by either one of the suggested mechanisms is accompanied by subordinate components parallel to the bedding planes. It may gain importance and become visible either in slippage of beds over each other, in tearing of beds due to lengthening, and in crinkling due to shortening. Accordingly, analyses of folding may make use of the criteria by which any one of the three conditions can be recognized.

Beds will slip over each other in a flexure fold as shown in Figure 18 A. This well-known fact has been described rather frequently (H. Cloos and Martin, 1932; Billings, 1942, p. 238). A lineation can be expected in the bedding plane normal to fold axes and without crinkling.

In a shear fold (Fig. 18 B) slippage is on cleavage planes and may be visible as lineation in *a;* it remains invisible if flowage dominates over slippage or recrystallization has destroyed the record. Different portions of a fold will show different symptoms. In Figure 18 B, the distance ab has been reduced to a′b′, bc has been lengthened to b′c′, and cd has been extended still more to c′d′. The crest of this fold will therefore show intense crenulation (*see* Scholtz, 1931; Lotze, 1932) which is impossible in the flexure fold of Figure 18 A. The upper limb may show boudinage with tearing of beds down dip and considerable elongation in incompetent beds (Wegmann, 1932; Corin, 1932).

This situation is considerably accentuated in Figure 18 C where flowage is added to slipping. Inside of the arcuate fold ab has been reduced to a′b′ and less on the outside. More crenulation should show on the inside than on the outside. bc is not changed profoundly, but cd is elongated, and de almost doubled. ee is not shown in Figure 18 C but lies to the right of d, a distance equal to c–d. d′e′ is more than twice the original distance, but elongation is due to placing of c and d, and elongation percentages are less than in the crest of the fold. A similar condition becomes apparent in Figure 18 D where extension in *a* results in stretching of the upper bedding plane in spite of flowage and lateral reduction of *c*.

So far the assumption has been made that aa, bb, cc, and dd in Figure 18 are parallel planes. There are, however, not many folds in which the cleavage dip remains constant from limb to limb. It fluctuates considerably about the general trend of the axes. South of Lancaster, Pa., the dip varies between 90° and0 ° (Cloos and Hietanen, 1941). In Montgomery County, Maryland, the dip fluctuates from

20° northwest to 60° southeast within 10 miles across the strike as is well known. In the Hagerstown Valley, cleavage varies between 20° east along the east side to 20° west along the west side and 90° in the central portions.

Fanned cleavage in a fold, however, complicates the deductions presented in

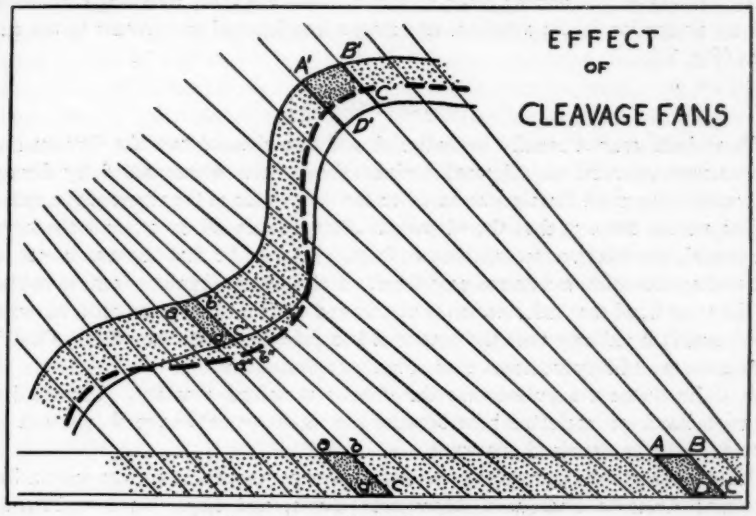


FIGURE 19.—*Effect of fanning cleavage*

Figures 18. If cleavage is a flow plane, diverging cleavage means diverging flowage toward anticlinal crests and converging flowage towards synclinal centers. In an area where movements are uniformly in one direction, the particles move farther apart as they move toward the crest of an anticline and closer together when moving toward the center of a syncline. This principle is illustrated in Figure 19.

The two parallelograms in the horizontal bed are almost of equal dimensions and are moved into the positions a′b′c′d′ and A′B′C′D′. Convergence in the syncline reduces ab and cd, but AB and CD are enlarged in the anticline. If the secondary positions are also treated as parallelograms the sides a′d′ and b′c′ should be enlarged to a″ a′ and b″ b′. With the slight convergence shown the thickening of the bed is 32 per cent. In the anticline similar treatment shows that the thinning of the bed is about 37 per cent. The new position of the bed is drawn as a heavy broken line.

Figure 19 holds true only if all portions of a bed have moved in the same direction as shown and claimed in shear folding. The other factors illustrated in Figure 18 have to be combined with convergence of flow planes where necessary.

As the material flows forward into anticlines and synclines crowding in the latter may prevent forward movement, whereas anticlines become loci of relief and easy progress. The tendency should thus be for anticlinal areas to form more readily, move more freely, and possibly attract material from areas of crowding and more intense pressure. In converging and diverging flowage in cleavage fans, anticlines

should form more readily than snyclines in areas of dominating laminar flow or shearing.

Many good cross sections show that anticlines surge forward, and synclines are left behind.

All sections of the western slope of South Mountain show crowding crenulation, intense elongation in the syncline, and rather free forward movements in the anticline (Fig. 20).

RECONSTRUCTION

Shear folds cannot readily be flattened and straightened out like flexures since movements occurred on subparallel planes have been accompanied by flowage. Reconstruction must therefore be based on the restoration of the ellipsoid to a sphere.

The author assumes that the ellipsoidal oöids contain all, or at least the largest portion of, the deformation resulting in folds. It could be that the matrix was still softer than the oöids and flowed past them. Deformed mud pellets seem to indicate on the other hand that deformation of matrix and oöids is of the same order of magnitude, and it is unlikely that the matrix is less deformed than the oöids. Oöid deformation most likely indicates a minimum of deformation.

It is furthermore assumed that the volume remained constant. The third dimension has been neglected here because the measurements have shown that *b* is changed little or remained unaltered.

Plate 13 shows the principles of reconstruction as applied to a cross section from Potomac River to Boonsboro, Monument Knob, and High Knob in Frederick County.

Oöid deformation is more than 100 per cent and increases eastward. Cleavage is persistently parallel in the entire uplift. Cleavage is flow plane as shown in the oöid analysis and has been taken as reference plane for the whole area (X Y of Plate 13).

The fact that the volume remained unchanged is expressed as follows: if r is the radius of the sphere, and a, b, and c the ellipsoid semi-axes:

$$\frac{4}{3}\pi r^3 = \frac{4}{3}\pi abc$$

thus

$$r^3 = abc$$

If

$$b = r = \text{constant}$$

$$ac = r^2$$

This formula has been used in the reconstructions on Plate 13.

Ellipsoids in section 1 of Plate 13 are constructed from oöid data. Cleavage dips east consistently between Tilghmanton and High Knob. The section is an *ac* section, and *b* is normal to the profile.

X Y is a line parallel to cleavage, and the section has been constructed from here

upward and eastward. To the west cleavage dip becomes steeper, and only that part has been used in which cleavage is parallel.

In section 2 of Plate 13 the construction is carried out for 18 points at 10 per cent intervals. Deformation is 182 per cent in terms of increase of the a axis beyond r. The distance from X Y to A is the diameter, 2r, because it includes the whole area considered. As long as A remains in the horizontal bed at a distance 2r from X Y deformation is O, and a = r = c. When A begins to migrate toward its present position A′, c grows smaller, and a increases according to the formula. At the beginning a and c change at almost equal rates. As deformation grows beyond 100 per cent small changes of c will move a at a much higher rate toward A′, and movement is almost entirely "forward" and in the direction of cleavage and *a*. The equivalent point of A is where the hyperbola meets the section at 182 per cent.

The same general principle is also shown in the upper right hand corner of Plate 13. The restoration of oöids is here shown in 2 stages: first is the restoration of c and second the reduction of a. The mathematical solution of this process is section 2 of Plate 13.

The total increase of a has been plotted in one direction because it is assumed that the movement was forward, not stationary, and in a downward and upward sense simultaneously. The direction of escape is forward and upward and has thus been interpreted. The position of X Y is arbitrary but not important as long as the horizontal hinges in X Y and the bed to be considered. Any point in that surface will fall into the section in its equivalent position if properly constructed. A new normal has to be constructed for every point considered, and this normal supplies a new value for 2r.

Section 3 is an attempt to determine the thickness of the section. B and C are two points above each other approximately at the base of the Tomstown (B′) and the base of the Weverton (C′). If the two points are then moved to B′C′, the distance B C will change as shown for every 10 per cent of deformation. B C more than doubles which is expected with oölite deformation exceeding 100 per cent and increasing eastward. Conversely if the distance between two points in an observed section of such a fold is to be measured reconstruction has to proceed in the same manner, and, if the deformation ratio $\frac{a}{c}$ is known, should reach a = c = r, at which stage the two points of the section should be above each other, their distance indicating, the thickness.

A rough estimate of the order of magnitude of reduction of the thickness can be made by reducing the thickness parallel to the cleavage along X Y by the amount measured in the oölites. The thickness is then measured as the vertical component. This construction assumes also that movements are on subparallel planes during the entire deformation and that the fold is a shear fold without flexure. (*See* Figure 18 B.)

Increase of thickness is accompanied by reduction of width as shown in section 4. Here two points A and C in the same bed are traced along their paths towards the fold, and their relative movements are shown as dotted lines connecting corresponding percentages of deformation. Up to 100 per cent distortion the movement consists

largely in lateral transport combined with lateral shortening and thickening, folding, and beyond that point, in tilting of the bedding plane which must be most intensely crinkled at that stage.

Section 4 of Plate 13 demonstrates the peculiar fact that lateral shortening may be intense without equivalent obvious folding or tilting of strata. It seems unlikely, however, that such deformations remain undetected even in unconsolidated or little consolidated sediments.

The effect of shear folding on stratigraphic thicknesses is further discussed below.

The mathematical construction of these results is accurate, but the assumptions made are many. The cross section (section 1 of Plate 13) is constructed from field data which are limited to the surface and are also open to interpretation. In constructing the section, oöid measurements have been used. A reconstruction and interpretation is attempted more to suggest an approach than to present results. The result indicates, however, that some of the present standard concepts and premises are badly in need of critical inspection.

THE SOUTH MOUNTAIN FOLD

The South Mountain fold is an excellent example of a large shear fold with laminar flow as illustrated in Figure 18 B.

The deformed oöids prove that the flow planes are cleavage planes and that considerable movement took place on cleavage. Laminar flow is the principal mechanism of folding and oöid deformation, for it is movement on subparallel planes and thus of equivalent effect as slip in many closely spaced subparallel shear planes.

Intense cleavage prevails in the entire fold including the volcanics of the core. Its strike and dip are constant in all parts. The South Mountain plan is typical of the entire area with only minor differences of geographical orientation. Toward the west the mutual relations of structures is the same. Orientation changes and cleavage disappears in the limestones but is intense in the Martinsburg shale.

Oölites are restricted to a small area in the western foothills of the uplift, but the consistency of the deformation plan and its orientation justifies generalizations which include the entire structure.

There is no structural discontinuity between the volcanics and the Paleozoic rocks above.

Figure 20 shows four cross sections through the western slope of South Mountain in Washington County, the writer had more data available here than in the northern continuation in Pennsylvania.

The orientation and ratios of the black ellipses are meant to indicate the position of the oöids in cross sections (*ac*). The heavy broken line marks the bottom of the sedimentary section and the top of the volcanics. The basic data for the sections can be found in the geological map of Washington County 1:62, 500 published by the Maryland Geological Survey in 1941.

The South Mountain fold is a large asymmetrical structure that pushes northwestward and westward over the underlying Paleozoics and exerting its influence about 5 to 8 miles beyond its crest. The sediments are thrown into a number of intricate

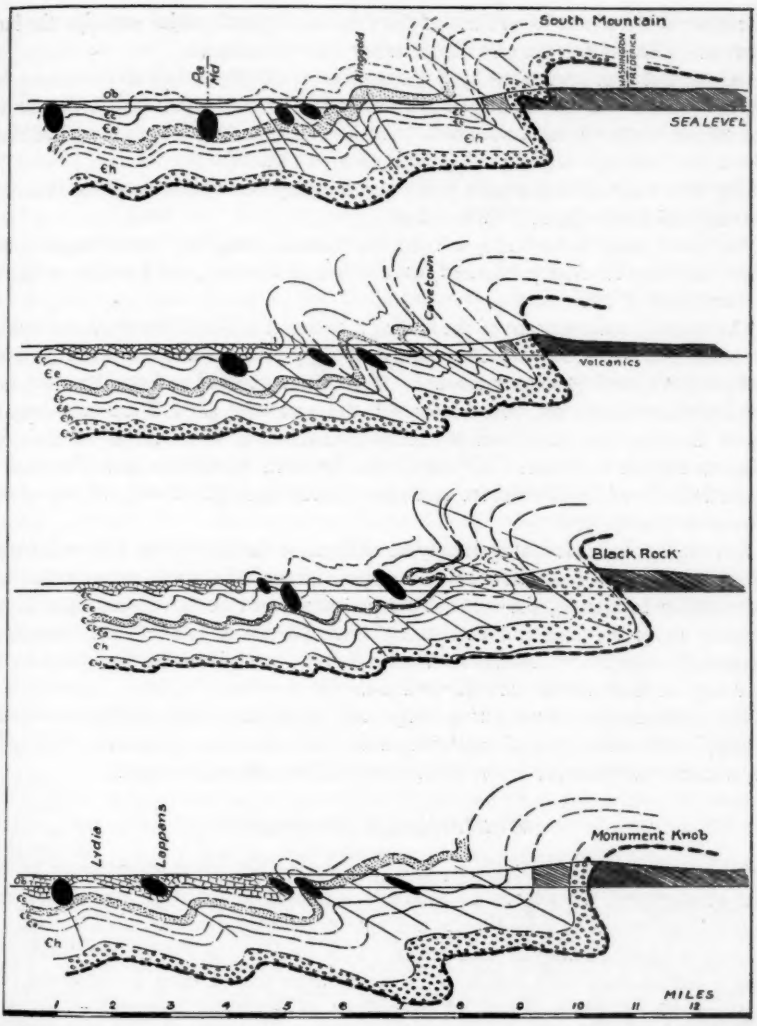


FIGURE 20.—*Four cross sections through the western slope and crestal portion of the South Mountain fold*

Black ellipses are constructed from oöid measurements.

and in part recumbent folds with gently eastward-dipping axial planes. Cleavage dominates the section as long as deformation is fairly intense. Beyond the influence of the fold the oölites begin to righten themselves, and cleavage disappears in the limestones. Within individual layers like the Tomstown, Waynesboro, and all other formations many small folds appear in the field that cannot be shown in the sections.

The general dip of the lower limb of the syncline is gentle which explains the large areas occupied on the map by these rather thin formations.

Large thrusts as postulated by Jonas and Stose (1938) do not seem to exist, but the movement is distributed over the entire section and taken up in the flowing and soft sediments along a wide belt. Small reverse faults occur as near Smithburg where the Antietam sandstone has been sheared out.

The limestones of Hagerstown Valley are in many small folds mostly with a steep western and gently-dipping eastern limb.

The lowest point in the Valley is in the Martinsburg shale at Conococheague Creek, where cleavage is most prominent, usually nearly vertical, and bedding undulates in many small folds.

The horizontal component of the folding movement is about five times the vertical in section 3 of Plate 13. The distance travelled by points B and C is about 16 miles, and point A moved 14 miles westward. The section exposed at Boonsboro was thus originally near Frederick, Md. However, the area west of X Y has also been reduced laterally, and the South Mountain fold followed westward as all the other folds to the west formed. Reconstruction between Boonsboro and Frederick is only relative, and the Boonsboro section originated probably in the vicinity of Baltimore or Washington.

The vertical increase is surprisingly small because the movement follows the maximum extension of a at a low oblique angle. If the axial plane were vertical and deformation as intense, the vertical components would be $2a-r$ and equal to the distance above the normal in section 2 of Plate 13. Such folds do not exist unless diapir folds may be thus interpreted. A salt dome or an intrusive body of a similar kind may be the result of such deformation.

The postulated movement is flowage, and large horizontal displacements were accomplished without loss of continuity and with only minor thrusting. The major adjustment was absorbed in the thickening and crenulation of strata.

STRATIGRAPHIC THICKNESSES

At an earlier occasion (E. Cloos, 1942) the author has called attention to the fact that stratigraphic thicknesses as generally measured in the field may include considerable distortion in folded areas and that such measurements cannot always be trusted to represent original thicknesses. It is necessary to analyze the deformation that a section may have suffered to a much larger extent than is customary, since stratigraphic thickness enters all discussions of depths of geosynclines and stratigraphic correlations.

As far as the author knows there are very few if any sections which include analyses of distortion, unless it is so intense that it has led the author to conclude that measurements are hopeless due to recrystallization.

The attitude of beds is rarely indicated which renders construction of cross sections impossible, and the reader must depend entirely on the interpretation of the author as shown in his sections.

Due to the deplorable habit of omitting structure symbols in maps many authors have also not indicated cleavage attitudes. This makes an appraisal of possible

distortion due to folding impossible. The practice to record geological evidence only selectively and incompletely is objectionable and has been partly abandoned by paleontologists and mineralogists-petrographers who measure dimensions of fossils or refractive indices respectively. There is little use, however, to be accurate to the third decimal in the fabrication of bricks if the architect omits the use of plumb line and rectangles in the construction of the house.

Analysis of the South Mountain fold shows that all the stratigraphic thicknesses in the area are distorted. In many sections this distortion can be shown directly and is demonstrated in Figure 21 A–C.

In Figure 21 a block of constant volume has been deformed up to 100 per cent, thus the bed becomes thicker as the block becomes lower. The third dimension remained unchanged.

Distortion of sections varies, however, with its position in the fold. Oölite extension normal to, or at large angles to, bedding is common because vertical beds are encountered along the western slope of the uplift and are near the crest of the fold as shown in Figure 20. Cleavage dips gently east.

All observations on oölites prove that in the South Mountain fold maximum extension is in the cleavage plane and also normal to the fold axes. In the limestone, cleavage appears where oöid deformation exceeds approximately 20 per cent. In the shales it becomes visible earlier. This may mean then that cleavage at a large angle or normal to bedding indicates increased sections. It would be of considerable interest and importance to determine relations between cleavage, bedding, and stratigraphic thicknesses systematically at many localities.

Few stratigraphers and geologists include statements on cleavage, an indication of its intensity, angular relation in space, or its relation to bedding.

The many obvious fluctuations are meaningless without such information. They may not be due to differences in depth of deposition but may be a function of distortion due to folding particularly if diastrophism introduced diagenesis.

This relationship is most important and rarely recognized as a problem. It means, however, that where soft sediments have been folded traces of deformation are obliterated later, and a stratigrapher may never suspect distortion.

Undistorted fossils may indicate lack of deformation, but they may also have been hard-shelled fossils in a soft matrix like the calcite pebbles and crystals in the oölites.

Thickening in anticlinal crests is well known, recognized easily, and pictured frequently. It proves that beds have thickened at a large angle to bedding and that it may have done so at many points without being detected. In the presence of cleavage great care is called for. As shown in the previous chapter thicknesses cannot be measured in shear folds without proper reconstruction.

The presence of enormous quantities of shallow-water sediments in the Appalachian geosyncline is puzzling and as yet unexplained. It cannot be accounted for by subsidence of the bottom in isostatic adjustment alone. All sediments are thicker here than outside. Geosynclinal folding and thick sediments have been linked frequently, and folding has generally been attributed to areas with thick sediments.

It may be worthwhile to appraise these premises and to find out in every case whether folding took place in troughs with thick sedimentation or whether sediments may be thick due to folding.

FIGURE 21.—*Elongation and bedding*

A: block diagram of undeformed oölite. B: deformation 50 per cent. C: deformation 100 per cent. The block is doubled in width and half as high. Bedding shows intense crenulation and has also doubled in thickness

SUMMARY, CONCLUSIONS, AND OUTLOOK

Investigation of oöid deformation in a fairly large tectonic unit has proven to be a fruitful enterprise, even if it seems time consuming and intricate. The author had to devise a suitable method of investigation and computation and feels certain that in the future many short cuts and improvements will expedite procedure at many points.

The region is particulary suitable because the author had mapped a portion of it prior to the present investigation, and geologic maps were available for most of it. The distribution of deformation ratios varied so much with respect to major tectonic units that the study remained always interesting and furnished results.

Detailed research of this kind which is not undertaken to provide a geologic quadrangle or County map and report should be based on the best possible existing geologic map and not be burdened with routine work and collection of data which is not directly related to the study.

The study of mutual textural relations under the microscope proves that the oöids were deformed very early in the history of the rock and of the area and maybe prior to complete consolidation. Mineral growth on deformed oöids remained undisturbed by postcrystallization deformation and detrital grains, and pseudopebbles remained undeformed because they were enveloped in a soft and protecting matrix. Oöid deformation is closely related to the folding of South Mountain, and it is concluded that this folding took place also at a soft stage.

Regional variation of deformation intensities and orientation of axes of distortion indicate the existence of a uniform master plan at a very early stage and for the entire area and exclude the possibility of local and accidental directions. The South Mountain plan is unaltered in an area of at least 300 square miles.

Measurements of deformation of the third dimension (*b*) has recently been stressed in the literature. The oölites show little distortion in that direction, and the two prevalent lineations are due to cleavage-bedding intersection in *b* and flowage extension in *a*. The latter is the more pronounced structure and common also in the entire uplift including the volcanic core.

Crinoids can be used in nonoölitic rocks but demand a slightly different technique. Their wide distribution in limestones and shales may make them more useful than oölites.

Particular attention has been paid to the possible existence of two deformations as explanation of the strong lineation in *a*. There is no evidence for more than one act of folding, and the lineation is due to flowage.

Cleavage is not a shear plane in the sense of Becker's theory or one-sided shearing according to Schmidt or Sander but is defined by the maximum and mean axes of the ellipsoidal oöids. It is explained by laminar flow in subparallel planes and supported by the microscopic findings which show that oöids must have been distorted in a plastic condition. Axial-plane cleavage dominates the uplift but parallels the axial plane only in the crest of the fold. Cleavage forms a fan which opens toward the anticlinal crest. Since the fold is asymmetrically overturned westward, cleavage dips constantly to the east and southeast.

Lineation is a flow line within a flow plane.

Oöids are not strain ellipsoids because they violate all restrictions which confine the strain theory. They are nevertheless useful as indicators of extent and direction of deformation and provide a sound basis for deformation analyses.

Fractures occur at a postflowage stage. They show that folding continued into consolidation and until fracturing became possible.

South Mountain is interpreted as a large shear fold due to flowage in subparallel planes and with only subordinate bending of strata. This is based on the existence of these planes in the entire uplift and their simple relationship to the axes as recognized in the cölites. Reconstruction of the fold shows intense lateral shortening with comparatively little uplift due to the inclination of the flow plane roughly parallel to the theoretical path.

Stratigraphic thicknesses cannot be measured in the area where subparallel planes govern the deformation—whether they are flow or shear planes. Distortion is not in reference to a center of curvature but to an oblique plane. Oöid deformations prove lengthening in the cleavage and reduction of dimension normal to cleavage. Before thicknesses can be appraised, the distorted oöid has to be restored to a sphere, and the displacement on flow or shear planes must be reduced. If this is done, thicknesses differ substantially from those met in the field.

Reconstruction of the South Mountain fold shows that original thicknesses were most likely only about half of the present ones. This is substantiated also by the direct observation that oöid elongation is frequently at a large angle to bedding.

Such distortions are not necessarily recognized in the field if deformation preceded consolidation because postdeformational crystallization will mask structures unless they are preserved as in oölites. Hard and resistant forms, however, may record nothing like pseudopebbles and detrital crystalline grains. Hard-shelled fossils may also show that no deformation has taken place, and therefore thickening will not be suspected.

Other symptoms may indicate distortion. Bedding may be crenulated and show a lineation, or cleavage may indicate flowage. Wherever cleavage is at a large angle to bedding the author would conclude distortion of thicknesses as in all slates and slaty shales and question the stratigraphic measurements.

The average geologist is not inclined to record cleavage and other structural relations when measuring thicknesses of sections. No textbook suggests it. These structures should be recorded however and report even if they do not seem significant at the time. They belong to a complete record, and some other worker may be grateful in the future.

This study should be continued—which the author hopes to do as well as to interest others in similar research. Other areas contain deformed oölites which should be measured systematically. Fossils may also be used, particularly crinoids. Pebble deformation is common, has often been mentioned, and should be traced regionally and through structural units.

The position of cleavage in folds bears careful inspection and the determination of elongation in *a* or *b* in relation to cleavage is a promising and important field.

Deformation of rocks has been emphasized, but the author feels that many im-

portant questions can be investigated better in the analysis of deformation of non-crystalline and only partially deformed rocks. Crystalline rocks may be metamorphic rocks, but there is no visible or known unconformity, hiatus, or discordance between the crystalline rocks of the Maryland Piedmont and overlying and identifiable Appalachian Paleozoics. There is a gradation from fossiliferous unfolded sediments to folded (Appalachian) Paleozoics and from here into the crystalline schist of the Washington-Baltimore or Philadelphia area.

The oölites are probably in a most critical position between the nontectonites and tectonites (Fellows, 1943) or between those rocks that owe their texture to deformation (tectonites) and a less-deformed zone where rocks are truly undeformed even if folded.

There are innumerable smaller questions that need study and many important ones that bear on our present thinking on mountain building, isostasy, and crustal deformation.

There has been much discussion of so-called fundamental research, but what could be more fundamental than a systematic and critical reconsideration of some of the premises which enter into almost all interpretations of crustal deformation?

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Manuscript Received by the Secretary of the Society, August 22, 1946
Project Grant 375/41